**Basics of Mechanical Engineering-2**

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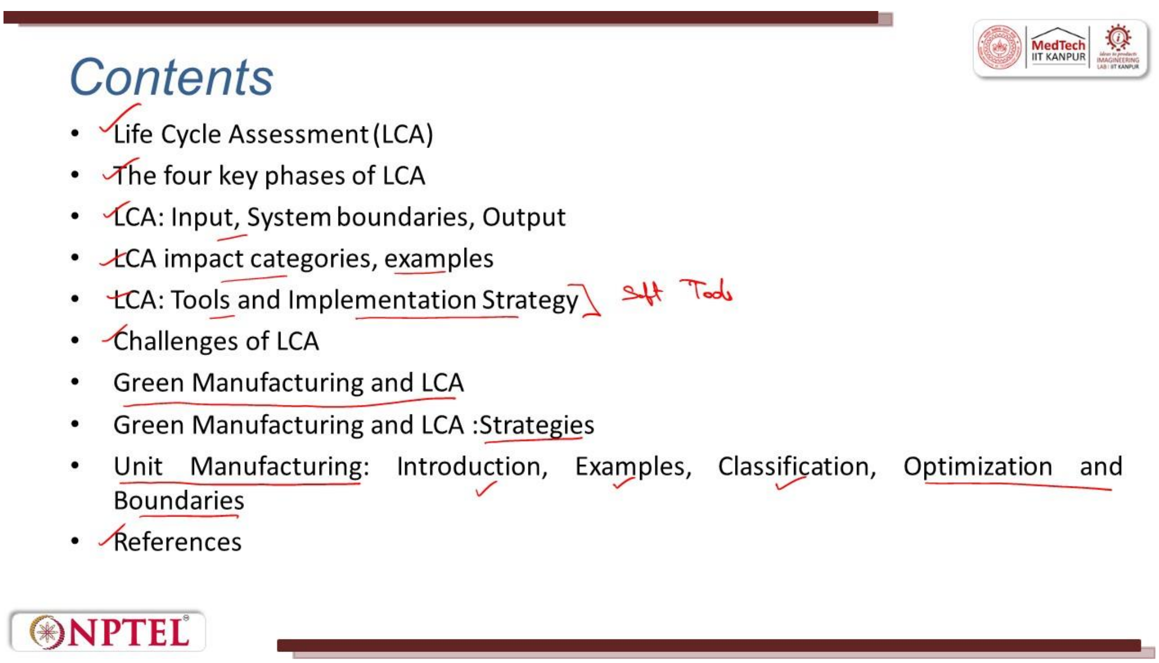
**Week 11**

**Lecture 49**

# Life Cycle Assessment

Welcome to the next lecture in the last week of the course Basics of Mechanical Engineering 2. We are discussing an introduction to sustainable manufacturing this week. This lecture will focus on life cycle assessment. I gave you an introduction to what sustainable engineering is and what sustainable manufacturing is. How green manufacturing is part of the overall sustainable manufacturing, and what its components and major drivers are.

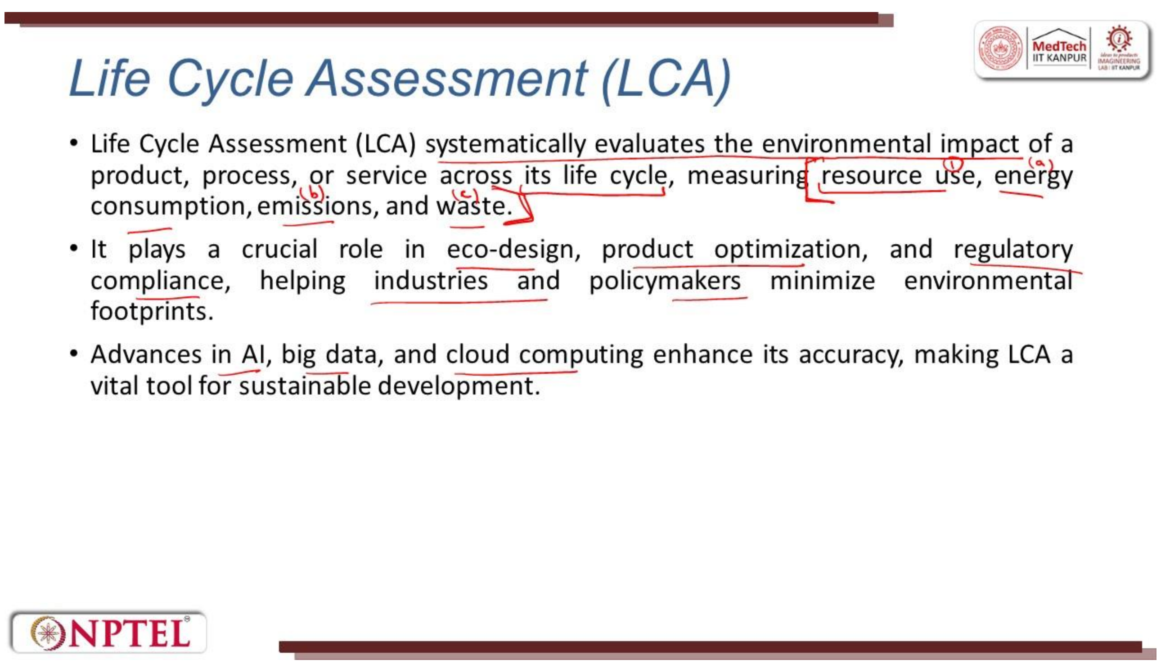



In this lecture, I will walk you through the Life Cycle Assessment phases, elements, and steps or stages through which we conduct it. The four key phases of life cycle assessment will be covered, and then we will see what the inputs, system boundaries, output impact categories are, along with some examples of life cycle assessment tools and implementation strategies.

We will also talk about recent software tools. We will explore the challenges in collecting data, assessing data, and understanding the impact. And how green manufacturing is connected to life cycle assessment.

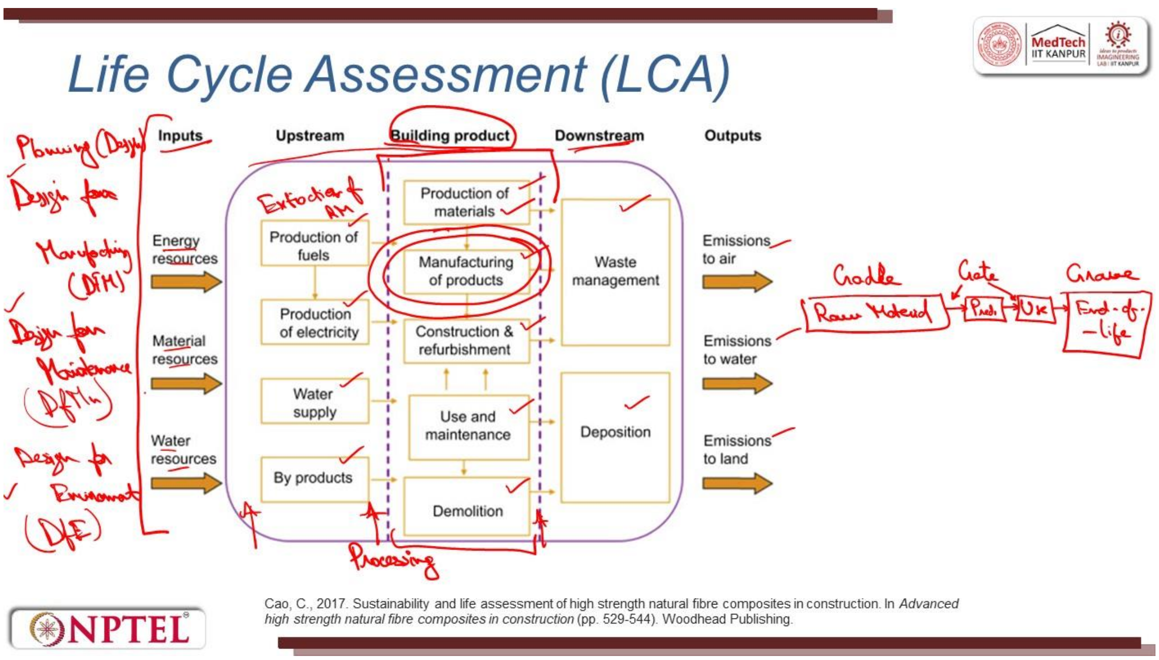
We will also discuss the various strategies currently being followed in green manufacturing. Then we'll take a quick glance at what a unit manufacturing process is. As part of the overall manufacturing system, when we go to the basic micro-level or unit-level system, what does that entail?

We'll try to see an introduction to this, examples, and classification of unit manufacturing processes. And how we use the different classifications and parameters in unit manufacturing processes to optimize. And I'll show you the references.




Life cycle assessment. Life cycle assessment systematically evaluates the environmental impact of a product, process, or service across its life cycle. Measuring resource use, energy consumption, emissions, and waste. So these are all factors which are measured.

Resource use could be energy consumption, emissions, or waste. It plays a crucial role in eco-design, product optimization, and regulatory compliance, helping industries. And policymakers to minimize environmental footprints or the one season. AI, big data, and cloud computing have enhanced its accuracy, making LCA a vital tool for sustainable development. As I told you in the previous lecture as well. There are certain tools and companies which are working exclusively on life cycle assessment.




Life cycle assessment is something we talk about from cradle to grave. You see here energy resources, material resources, and water resources are inputs to a system. These are inputs, and this is our system, or I would say the overall processing happens here. This is the processing where it happens.

This is a block where processing happens. There are certain sub-blocks here. There is production of fuels, production of electricity, water supply, and by-products. So this is extraction. Extraction of, I would say, RM.

This is raw material. And then comes production of materials, production of products, construction and refurbishment, use and maintenance, and demolition. Out of this, we generate CO2. Waste and deposition. These are downstream activities, and these emissions go to air, to water, and to land.

Which I would like to put as cradle to grave. When I say extraction of raw material, extraction of aluminium. Aluminium is extracted as an ore, then by distillation methods, the ore is processed, and pure metal is taken out of it. Different grades of aluminium are extracted; that is the extraction of metal. Then this aluminium goes to different kinds of industries for manufacturing.

For utensils, for the components of the automobiles or so, these are taken. Then, duralumin, for example, is used for aircraft manufacturing, so those are all taken. Then comes the building product part. Where we treat the materials as per our requirements. Such as heat-treated metal.

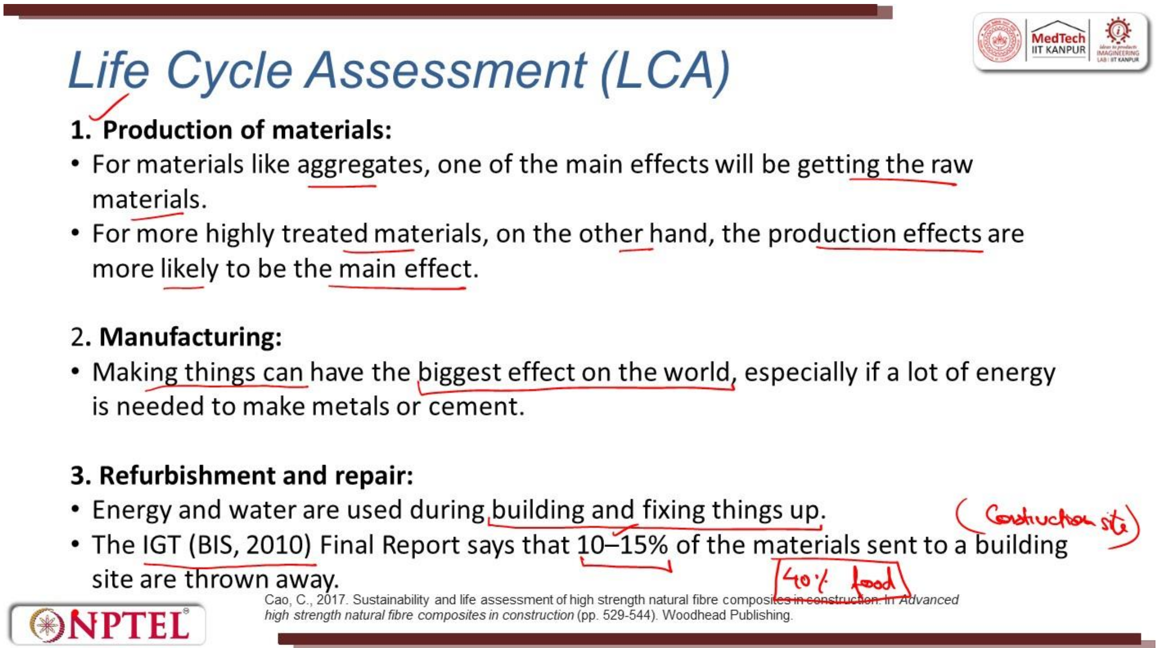
Aluminium is mixed with other metals to develop alloys. Those alloys are used here. And the manufacturing of the products is the major concern of our course here. When manufacturing is happening, all the processes that we have studied in the previous weeks,

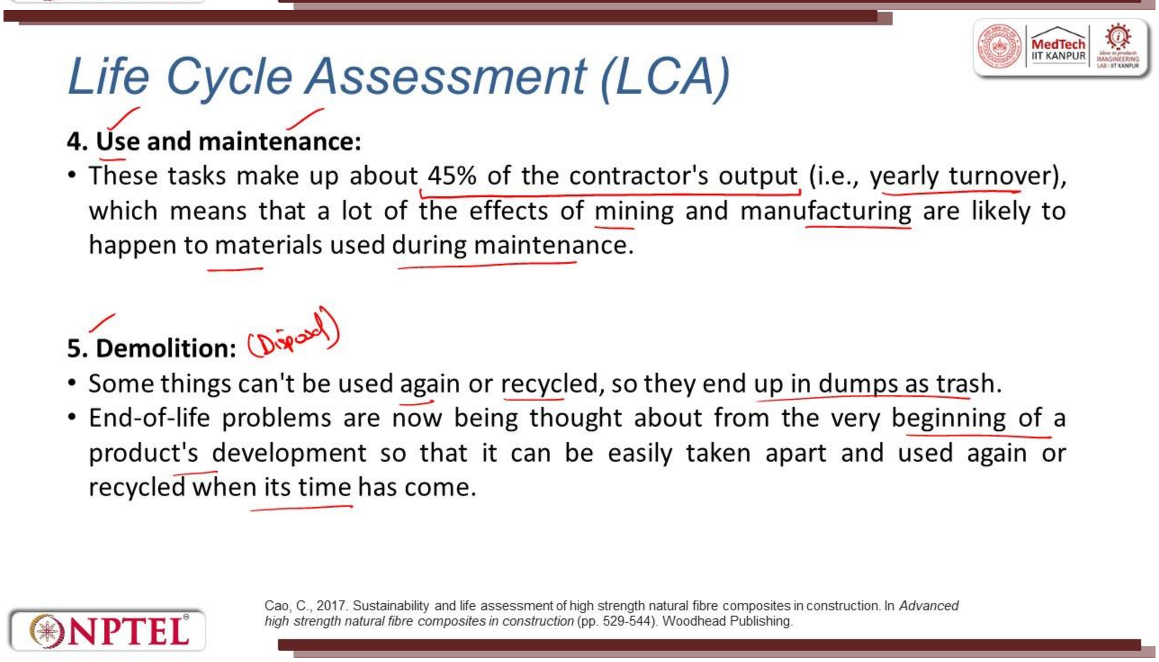
we use those here. And then construction, refurbishment, use and maintenance, demolition. I will come to this one by one. When I talk about cradle to grave, in between we have.

Multiple stop points for example here it could be a stop point. It could be a stop point here could be a stop point. We call it as stop point or halt points we call it as gate. So what happens in the cradle I will say it is a very beginning the raw material. And grave is finally the end of life.

End of life that is disposal. In between, we can have production. I will just production here or I can have the use production when the product is produced. Use is when the product is being used by the user. So, these are the gates.

This is a gate. From cradle to gate or gate to grave or from maybe gate 1 to gate 2, gate 2 to gate 3. Certain gates are there or certain steps are there in which we can put our scope of the life cycle assessment. What kind of assessment we wish to do? So, now let me see in the building of the product, what are these five major stages here.




First is the production of materials like aggregates. One of the main effects will be obtaining the raw materials for more highly treated materials. On the other hand, production effects are more likely to be the main effect. Manufacturing, which is of major concern, involves making things and has the biggest effect on the world. Because this is something we do most of the time, especially when a lot of energy is needed to make metals or cement.

Refurbishment and repair require energy and water during building and fixing things up. It is not only manufacturing; post-manufacturing refurbishment also happens. So, based on the IGT BIS standards, which are the Indian standards. The final report says that 10 to 15% of the materials sent to a building site are thrown away. Here, we are talking about a construction site, just as an example.

They say 10 to 15% of the material goes to waste. 40% of the food is wasted, whatever is produced. So, these are all different streams I am talking about. But we may be focusing on manufacturing. Then comes use and maintenance.

This task makes up to 45% of the contractors output. We are talking about the construction only. Yearly turnover which means that a lot of effects of mining manufacturing are likely to happen to materials used during maintenance. When I say use A car is manufactured, a scooter is manufactured, that is manufactured.

Before manufacturing, raw materials come from different parts, plastic material, metals, and there are certain nuts and bolts are developed, ancillary used, provide those to us. And finally, maybe a car is manufactured. This car is used by the person. During use as well, there is a lot of data. So that use and maintenance part is being discussed here.

Then comes demolition or disposal. Demolition in the case of buildings, disposal in the case of any of the products that we can talk about. Some things can't be used again or recycled so they end up in dumpster trash. End of life problems are now being thought about from a very beginning of a product's development. So that it can be easily taken apart and used again or recycled when its time has come.

So the point is we need to have planning here itself. I will call it planning or I will call it the design that you do. So, design for manufacturing is known as DFM. That is, if you are designing a product, if I am designing this stylus. If I am designing this mouse, it has to be designed in a way so that it can be manufactured.

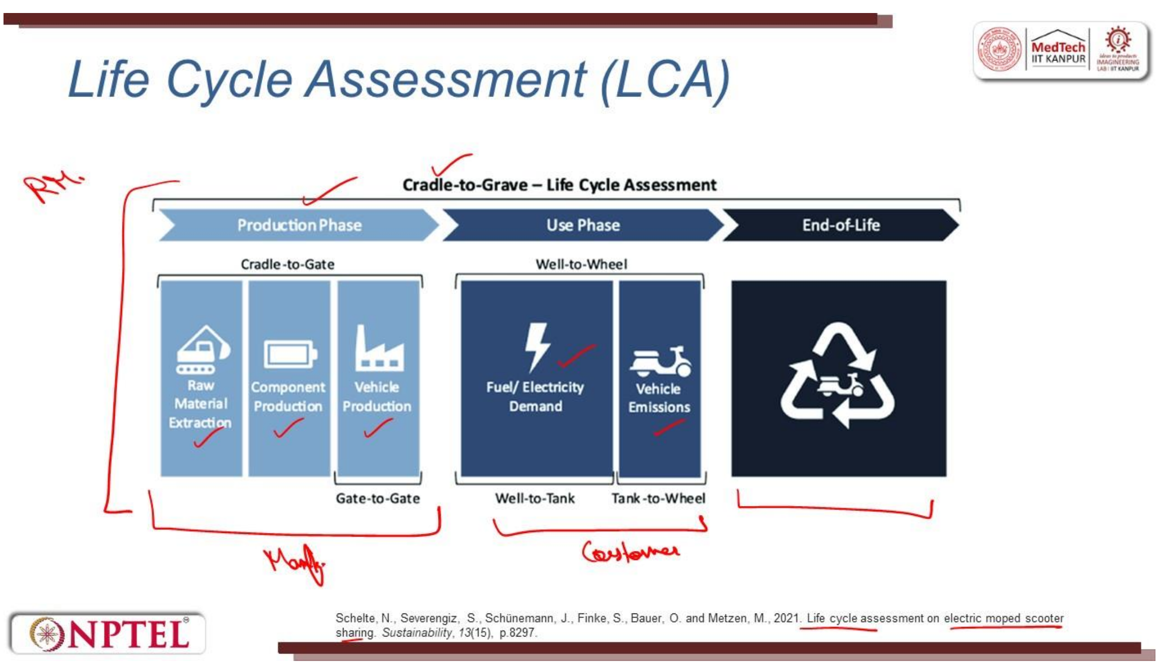
The shape could be properly developed through the process that we are using. We might be using injection molding. We might be using some CNC machines to develop or to cut the metal materials. So, designs have to be made so that they can be manufactured. Also, when the manufacturing has happened or manufacturing is going to happen.

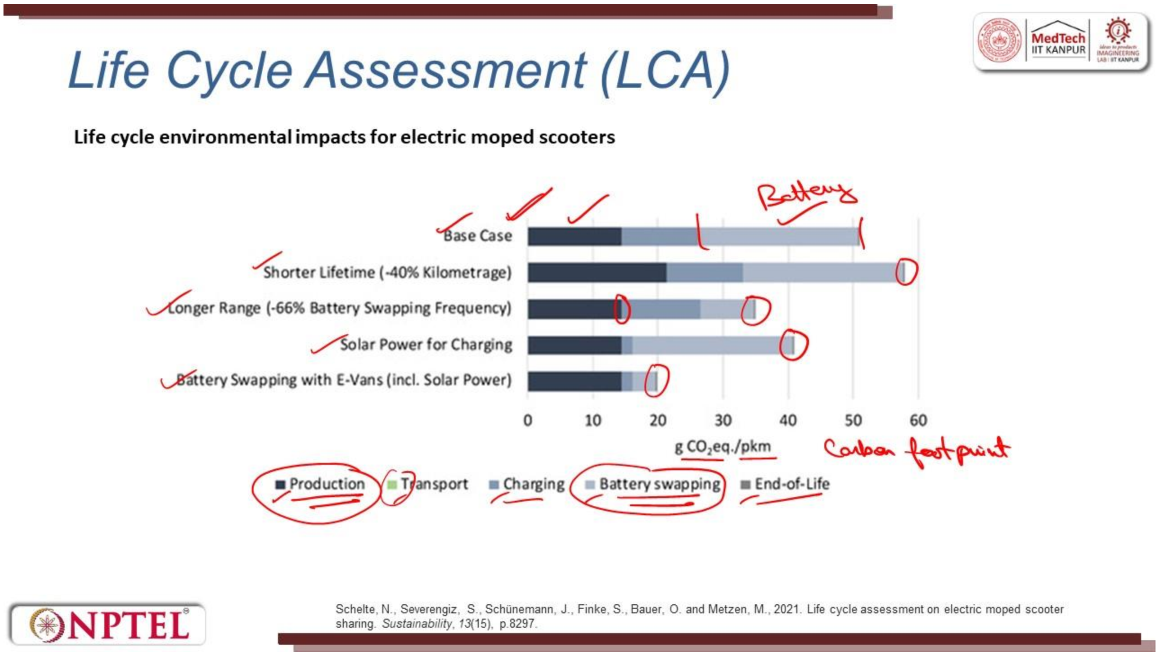
We also need to ensure that repair and maintenance are taken care of. That means the design that you are developing or making should be able to be maintained. So, design for maintenance is known as DFMN, design for maintenance. You get a car repaired as preventive maintenance every three months or every 10,000 kilometers. That is, the design has been made for maintenance, and overhauling happens maybe once in five years.

That is also designed for maintenance. Once in five years, this overhauling will happen and this regular preventive maintenance would happen each three months. It is designed for maintenance. Nowadays, when we talk about life cycle assessment, all designs are there. Design for assembly is also in between there.

That is the components should be able to be assembled and disassembled whenever required. The new term that has come nowadays is design for environment. Design for environment I will call it DFE which means the components that could be recycled that should be over put there. The components that could be reused could also be put there.

So that they can taken from be that product and put into the other product for you. For example nuts and bolts those could be reused in some other parts. Design for environment which means the disposal or the final end of life of the product. Should be plant in a beginning only what part would go to the solid waste. What part would go to the liquid waste also this is design for environment. So this is what life cycle assessment helps us understand.





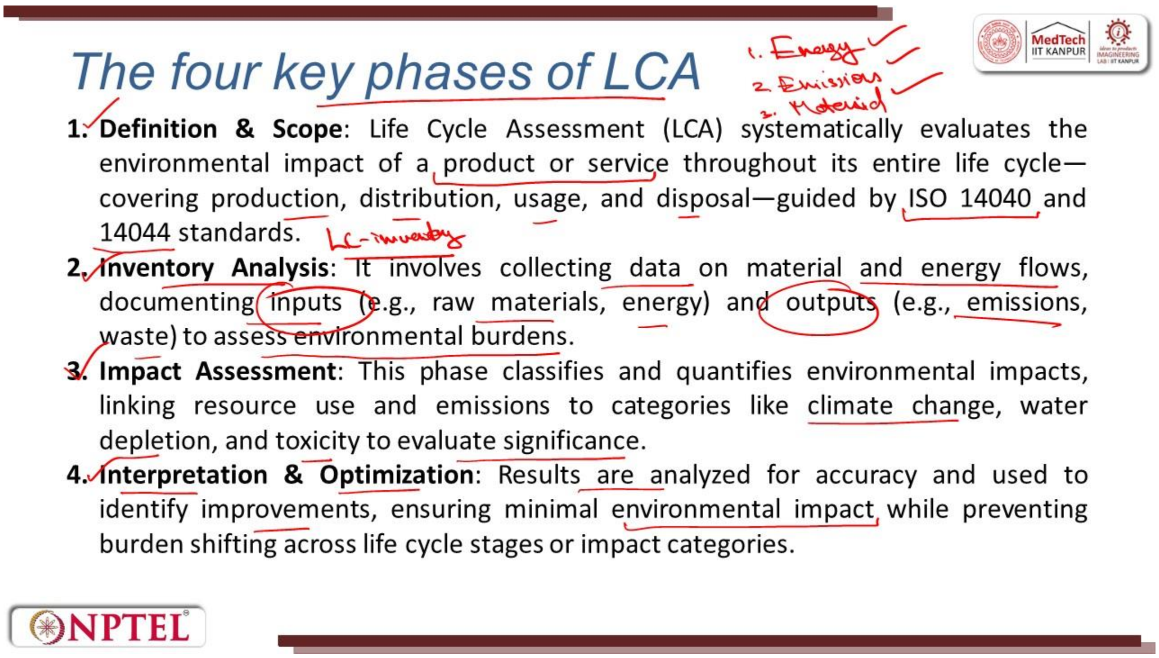

So this is a more detailed figure about cradle-to-grave life cycle assessment. This is the production phase, which includes raw material extraction, component production, and vehicle production. This is about vehicle production now. It has been taken from a study discussing electric motor scooter development.

Then comes the use phase, which includes wheel-to-wheel fuel, electricity demand, and vehicle emissions. So this is the production phase, which I am talking about—the manufacturing phase. And this is the use phase when it has reached the customer. That is, the scooter is being used by the customer. Finally, it goes to the end of life.

This is cradle to grave. Here we have extraction of raw materials even before manufacturing, as we saw in the previous illustration. In this case, some data points we can see from this study—the base case. You can see there is a legend available. This includes production, transport, charging, battery swapping, and end of life.

Majorly, you can see the environmental impacts which have been calculated using some of the tools of lifecycle assessment in either production. That is dark blue, or it is in battery swapping. That is in the use case; this is battery. That is written here: battery swapping, and majorly, it is production. Transportation is very minimal.

Just between production and use, there could be transportation. And you can see end of life is also a small part, as you can see; this is end of life. Which means majorly, the significant contributor to the lifecycle impact is production and the usage, that is, battery swapping. In this case, the certain pointers they have given are base case, shorter lifetime, 40 kilometers range than longer range, that is 66 percent battery swapping frequency, solar power for charging, battery swapping for events, etc. So this is the data that is taken from one of the studies, and the output is given in grams of carbon dioxide equivalent per kilometer. This is carbon footprint.




Now, let me talk about key phases of lifecycle assessment. First and foremost phase is definition and scope. Lifecycle assessment systematically evaluates the environmental impact of a product or a service throughout its entire life. Covering production, distribution, usage, disposal, guided by ISO 14040 and 14044 standards.

When I say life cycle, it is from cradle to grave. That is from the extraction of raw material to the treatment of the raw material. That is further used in manufacturing. Then from manufacturing to marketing. From marketing to customers, that is the use phase.

From the use phase to the reuse phase. Then from there, it goes to disposal. In between, we can define the scope. My scope or definition of the life cycle assessment that I'm going to study is only between the raw materials to manufacturing, only within manufacturing, or between manufacturing to marketing.

It could be major transportation from manufacturing to marketing, or between marketing to the customer, or during the use phase. This is how we define the scope. What is our definition? What are we going to focus on? Those are three factors.

Energy, emissions, material. What are we going to focus? 1, 2, 3. I am going to only talk about energy being used in manufacturing. I'm going to talk about the water consumption that is there in manufacture. We have to define the scope of the lifecycle assessment first.

Then comes inventory analysis. It involves collecting data on material and energy flows, documenting inputs. That is raw material, energy, and outputs, that is emissions, based to assess environmental burdens. I will talk about some tools or equipment or gadgets used to measure the energy consumption or the inputs and outputs in machining. That is the next lecture, green machining.

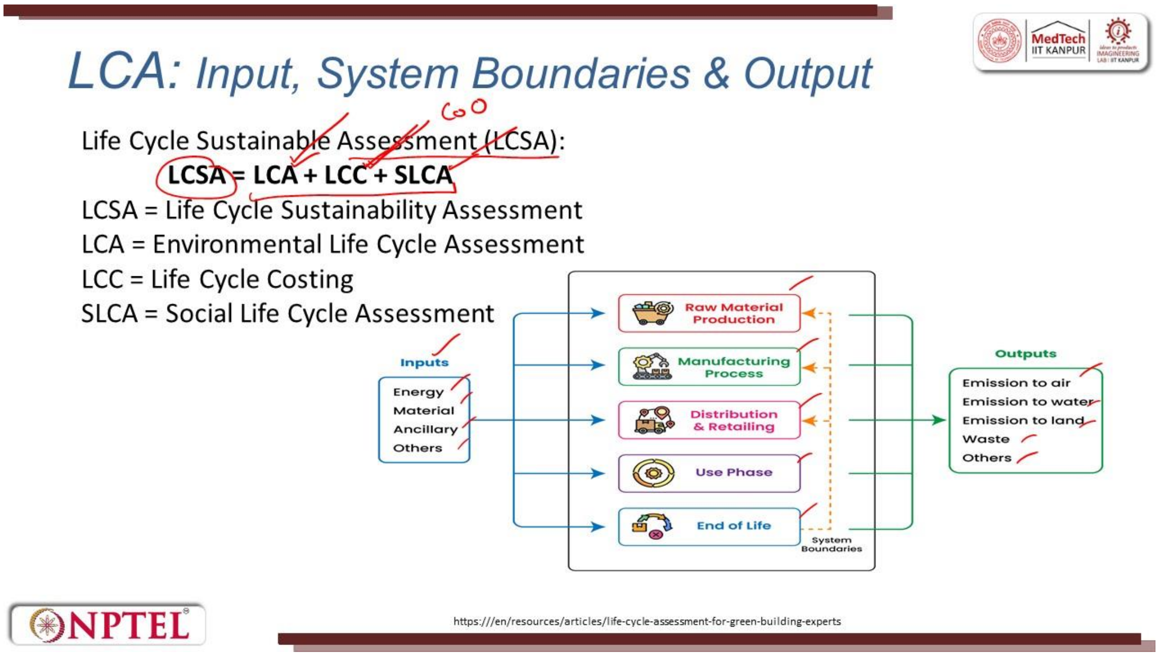
Now these are to be captured that is inventory analysis. This is not inventory that is raw material inventory we are talking about. When I say inventory it is life cycle inventory I am talking about. This is life cycle inventory. Life cycle inventory, which talks about these inputs, raw materials and energy and outputs, emissions and waste.

Then comes impact assessment. This phase classifies and quantifies environmental impacts, linking resource use and emissions to categories. Like climate change, water depletion, and toxicity to evaluate significance. Now, energy, emissions, material—whatever is in scope. That scope is being evaluated, and impact assessment is being conducted here.

Then comes interpretation and optimization. That is, results are analyzed for accuracy and used to identify improvements. Ensuring minimal environmental impact while preventing burden shifting across lifecycle stages or impact categories. So, what essentially happens when we rate our factory based on its greenness? That is required, based on the sustainability level that is needed.

If I say I just color my factory from red to green, red is the least green factory. Green is completely green—a fully net-zero factory. In between, I can have a range of colors: red, orange, yellow, blue, green, etc. Now, I have to first determine, based on certain criteria, where my present condition lies. What is the current scenario?

Suppose if I lie at orange, from orange, if I can move to yellow, that is my impact improvement. That is interpretation and optimization. In one step, I can go ahead. So, there are certain ways to do it. There are certain courses available on PTEL as well. You can visit those and try to understand more about life cycle assessment. Here, I will focus on mechanical engineering only.




Lifecycle sustainable assessment is just to establish a relationship for the complete sustainable assessment. It is some of the LCA + LCC + SLCA. These are different components that you can see.

Life cycle costing refers to the cost of ownership. The cost of ownership will be discussed in the last lecture. When I discuss the matrix of life cycle assessment or the matrix of sustainable manufacturing. What is the cost of ownership? It is life cycle costing.

And what is social life cycle assessment? This I will also talk about in the last lecture. So, total life cycle sustainable assessment is an aggregate of all these. Again, the inputs are energy, material, scenery, and others. They are raw material, manufacturing, distribution, use, waste, and end of life. And outputs could be emissions to air, water, land, waste, and others.

## LCA Impact Categories

1. **Global Warming Potential (GWP)** — The most widely adopted metric for analyzing environmental impact, GWP measures the impact of a product's greenhouse gas emissions on climate change, expressed in $CO_2e$ (carbon dioxide equivalents).

2. **Ozone Depletion Potential (ODP)** — Assesses the impact of chemicals, like CFCs, on the depletion of the ozone layer, which shields Earth from harmful UV radiation.

3. **Acidification Potential** — Evaluates the potential of emissions, such as sulfur dioxide and nitrogen oxides, to cause acid rain, affecting ecosystems, soil, and water.

4. **Eutrophication Potential** — Measures the impact of nutrient emissions, like nitrogen and phosphorus, on water bodies, leading to algal blooms and oxygen depletion.

NPTEL

## LCA Impact Categories

5. **Photochemical Ozone Creation Potential (POCP)** — Also known as smog formation potential, this category assesses the impact of volatile organic compounds (VOCs) and nitrogen oxides in forming ground-level ozone.

6. **Resource Depletion** — Examines the consumption of non-renewable resources, such as fossil fuels and minerals, and the potential for scarcity and economic impacts.

7. **Ecotoxicity** — Assesses the potential harm of chemicals and pollutants released during a product's life cycle on ecosystems and biodiversity.

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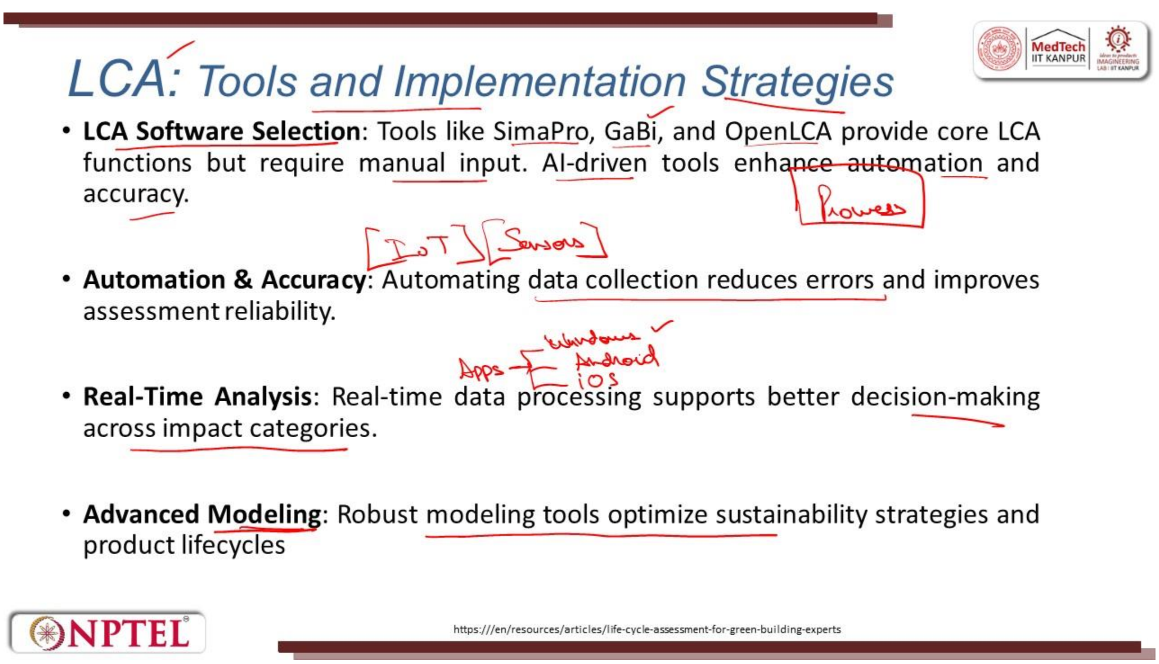
Certain impact categories when we are measuring the impact—to what level are we going to report it? First is global warming potential (GWP). The most widely adopted metric for analyzing environmental impact is GWP. It measures the impact of a product's greenhouse gas emissions on climate change, expressed in carbon dioxide equivalents.

When carbon dioxide equivalent—when we say the measurement base is carbon dioxide. If I say methane is also generated, if I say sulfur dioxide is also generated—methane. If 1 kg of methane is equivalent to what amount of carbon dioxide, that is taken. That is what is normalized based upon carbon dioxide. So, it is carbon dioxide equivalent that is taken as a carbon footprint.

Ozone depletion potential (ODP) assesses the impact of chemicals. Like chlorofluorocarbons on the depletion of the ozone layer, which shields Earth from harmful UV radiation. Acidification potential. Evaluates the potential of emissions, such as sulfur dioxide and nitrogen oxides, to cause acid rain, affecting ecosystems, soil, and water. Eutrophication potential.

This measures the impact of nutrient emissions, like nitrogen and phosphorus, on water bodies, leading to algal blooms and oxygen depletion. Some other impact categories are photochemical ozone creation potential. That is POCP, also known as smog formation potential. This category assesses the impact of volatile organic compounds.

That is VOC and nitrogen oxides in forming ground-level ozone. Resource depletion. That examines the consumption of non-renewable resources, such as fossil fuels and minerals, and the potential for scarcity and economic impact. Ecotoxicity assesses the potential harm of chemicals and pollutants released during a product's life cycle on ecosystems and biodiversity.



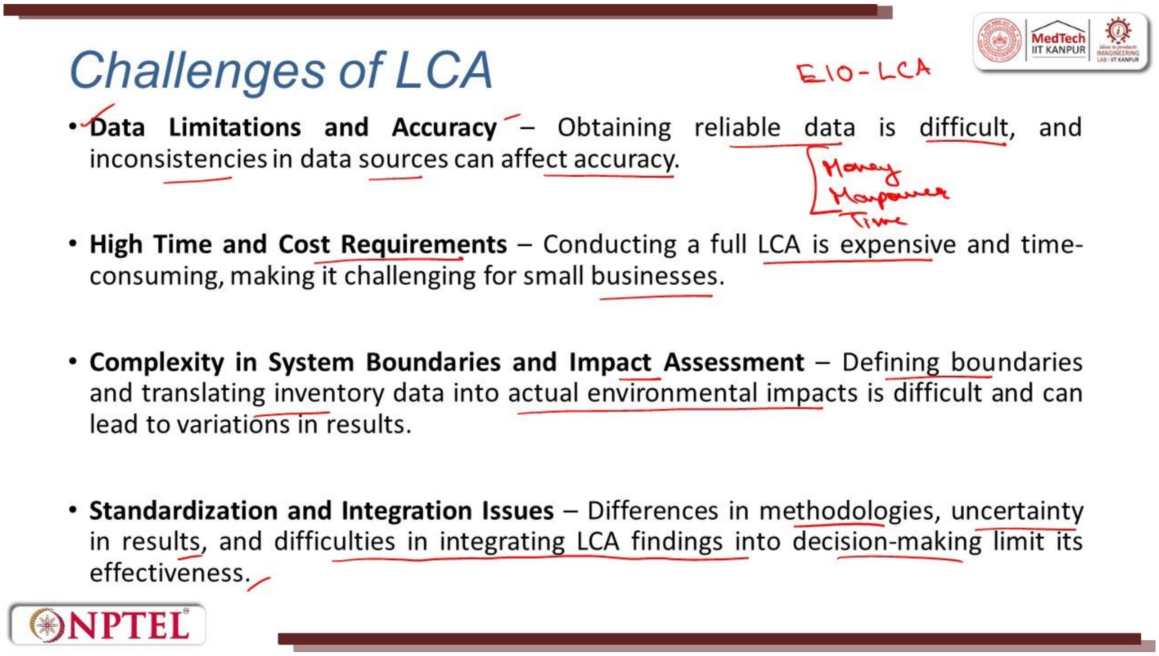

LCA tools and implementation strategies: multiple tools are now available in the market. There are certain software programs available that exclusively work on the assessment of the life. That is, the assessment of the life cycle of the product, the process, or the overall factory. Or maybe the kind of sector if you pick.

For example, if you try to pick the water-intensive factor. For example, in other industries, if you wish to pick the energy-intensive factor, that is the manufacturing of metals industry. Then, if you wish to pick maybe the agriculture industry, for those, different software systems are available. And there are also databases which are available, for example, Progress provides you the database. You might have to procure the database to have an assessment of what you wish for the certain LCA software selections that you could do.

There are tools like SimaPro, Gabi, and openLCA which provide core LCA functions. But they require manual input. The AI-driven tools enhance automation and accuracy. Data collection reduces errors and improves assessment reliability, that is, we use the Internet of Things. And we put sensors to collect the data. A real-time analysis while putting these sensors, you can also have a real-time analysis using the apps.

That could be the Windows apps, that could be the Android apps, or it could be iOS apps. These help us to have real-time data processing that supports better decision-making across impact categories. Then we have advanced modeling. That is, robust modeling tools optimize sustainability strategies and product lifecycle. Whatever apps we develop, for example, Gabi is one of the software that is there.

There is a GUI, graphical user interface. You input the data at the back and some calculations is happening. Those calculations are the algorithms which we are talking about here in modeling. Those models also, you can develop your own models, develop your own apps. There are tools which helps you to put your own data here.




But there are certain challenges when we talk about lifecycle assessment. Some of the challenges that I have listed here are data limitations and accuracy. Obtaining reliable data is difficult and inconsistencies in data sources can affect accuracy. Data when we talk about Secondary data data sources like I talked about progress.

There is data available in Gavi. Secondary data is an existing data. There is a tool or a website called as EIO LCA. That is economic input output life cycle assessment. They have the data.

But these available datasets or databases sometimes do not exactly meet the requirements that we have. For that, we have to conduct our own experiments. That is, we need to collect primary data. So, for reliable data, development or creation requires resources.

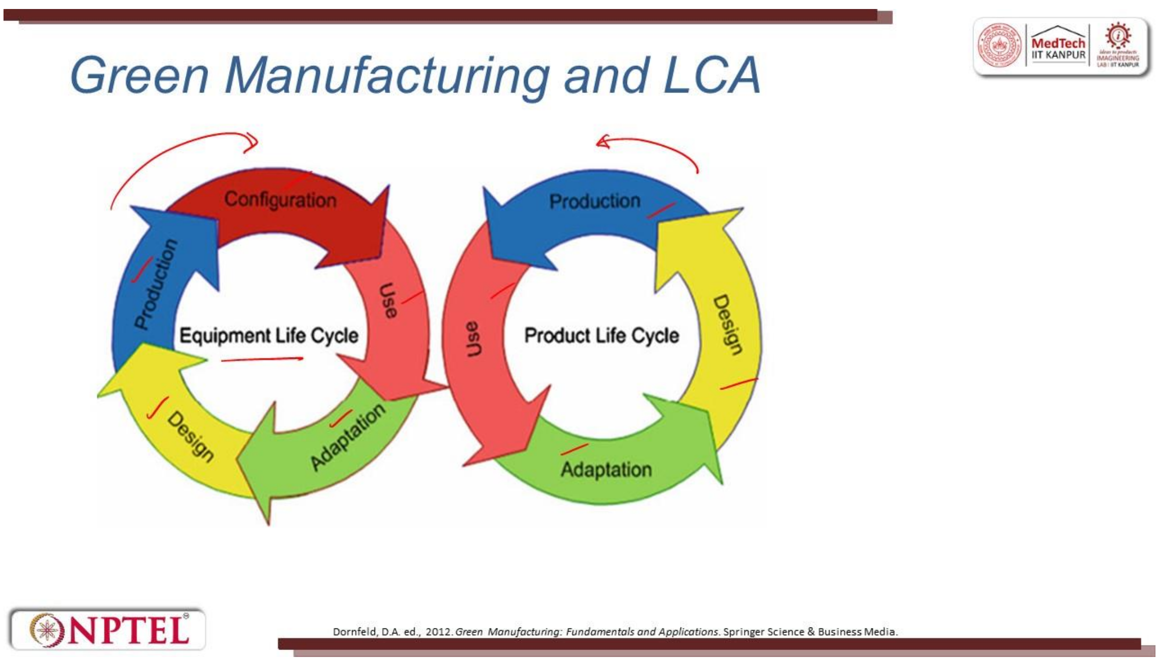
That is, it needs money. It needs manpower. And it needs time to collect the data. So, to collect the exact data, it is a very tedious job sometimes. That is one of the challenges.

Then, high time and cost requirements, as I have mentioned here, the resources required. Conducting a full lifecycle assessment is expensive and time-consuming, making it challenging for small businesses. Complexity in system boundaries and impact assessment. System boundaries—defining the boundaries. And translating inventory time to actual environmental data impacts is difficult and can lead to variations in results.

Standardization and integration issues, that is, differences in methodologies and uncertainty. Results in difficulties integrating LELC findings into decision-making, limiting its effectiveness with different kinds of tools. If you keep using different kinds of data collection methods, they are there. Those are difficult to confine to one specific decision or aggregate data. Or specific unit process data—there are different ways to collect it.

But we must first define or plan what LCA scope we are going to do. And what kind of impact we need to measure finally, then it is easy to do. Greenway factoring and LCA—if I try to amalgamate them. You can see this: we are talking about the life cycle of equipment, and this is the life cycle of a product. These two will run as gear wheels meshing together.

So here we have the design of equipment, production, configuration, use, and adaptation. Here also, we have design, then production, then use, and adaptation. These two go hand in hand—what are the things that come together?



## Green Manufacturing and LCA: *strategies*

**Strategies for sustainable manufacturing**

Strategies for sustainable manufacturing extend beyond environmental impact to broader industrial practices.

To manage emissions and waste, three main strategies exist:

**1. Pollution Prevention**

**2. End-of-Pipe Control**

**3. Environmental Restoration**

Material intensities for articulated industrial robot

| Articulated robot | | | Abiotic material | | Water | | Air | |
|---|---|---|---|---|---|---|---|---|
| Material | Unit | Amount | MI-factor | kg | MI-factor | kg | MI-factor | kg |
| Steel | kg | 828 | 7.63 | 6,318 | 56 | 46,368 | 0.41 | 343 |
| Stainless St. | kg | 63 | 17.94 | 1,130 | 240.3 | 15,139 | 3.382 | 213 |
| Copper | kg | 250 | 179 | 44,768 | 236.39 | 59,098 | 1.16 | 290 |
| Aluminum | kg | 219 | 8.11 | 1,776 | 234.1 | 51,268 | 2.93 | 642 |
| PVC | kg | 85 | 3.47 | 316 | 305.3 | 25,951 | 1,703 | 232 |
| Electronic | kg | 20 | 436 | 8,720 | 5,971 | 119,420 | 264 | 5.28 |
| Sum | kg | 1,465 | | 63,028 | | 313,061 | | 1,725 |
| Electricity | MWh | 60 | 1.55 | 277,939 | 66.7 | 4,914.201 | 0.54 | 35,482 |

Dornfeld, D.A. ed., 2012. *Green Manufacturing: Fundamentals and Applications*. Springer Science & Business Media.

Let me try to see some strategies here. Green manufacturing and lifecycle assessment strategies. Strategies for sustainable manufacturing extend beyond environmental impact to broader industrial practices. To manage emissions and waste, three main strategies exist.

## Green Manufacturing and LCA: *strategies*

**1. Pollution Prevention**

Controlling emissions before and during production by:

- Reducing material and energy use
- Using environmentally friendly materials

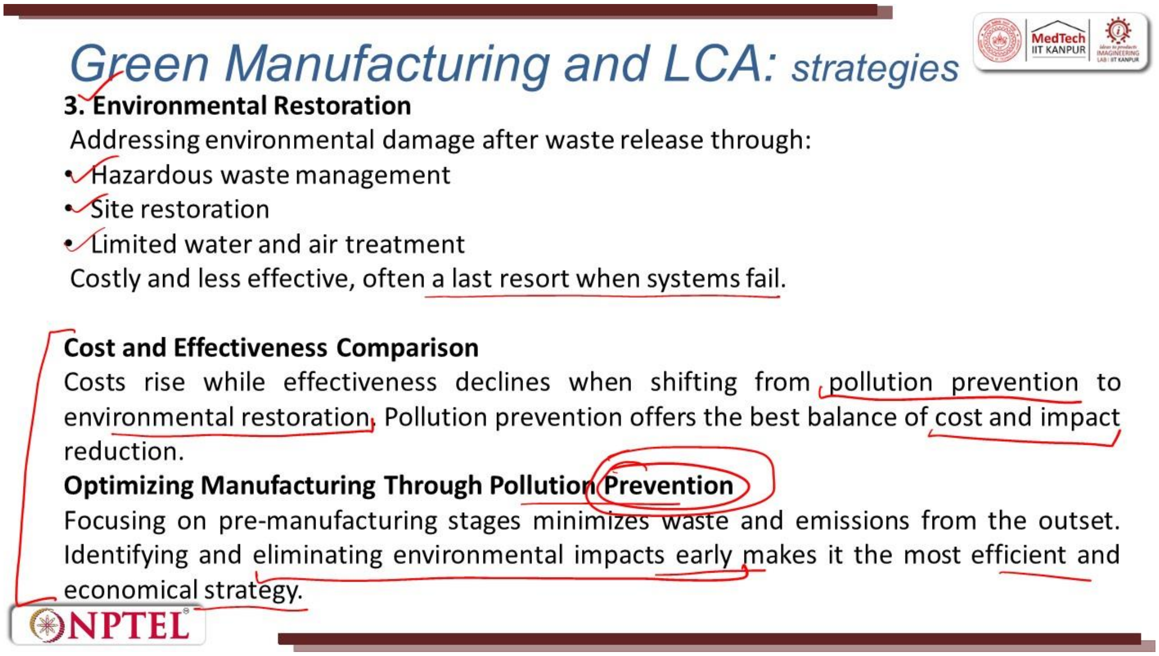
This approach is cost-effective and impactful, minimizing waste treatment needs.

**2. End-of-Pipe Control**

Managing emissions and waste after generation but before release through:

- Recycling
- Collection and filtration
- Waste treatment

Useful for retrofitting but less effective than pollution prevention as it manages rather than reduces waste.




That is pollution prevention, end of pipe control, environmental restoration. This is the table that gives you the intensity of articulated industrial robot. In which you can see the material is steel, stainless steel, copper, aluminum, PVC, or electronic materials are there.

The amount of material used is given here was specific robot that is being manufactured. This is also taken from a study here. And you can see the intensity of resources which are there. You can see the abiotic material that is given here in kgs. You can see water that is given here in kgs.

You can see air that is given here in kgs. So these are some examples when we collect the data this kind of the tabular form of the data you get from here. You can see in the terms of emissions in air in water or in a watering material. What are the material inputs now to talk about these three main strategies pollution end of pipe and environment. Let me give you a brief introduction.

Pollution prevention involves controlling emissions before and during production by reducing material and energy use and using environmentally friendly materials. I will discuss this in the next lecture for a specific green machining case. This approach is cost-effective and impactful, minimizing waste treatment needs. End-of-pipe control. When I say end-of-pipe, it refers to the flow of material systems from cradle to grave.

Managing emissions and waste after generation but before release through recycling, collection, and filtration. Waste treatment and recycling are examples, such as aluminum material used in cars. It is further recycled when the car is dismantled after the use phase. This material can be reused or recycled and converted again using casting or other processes. That we have studied into a usable form.

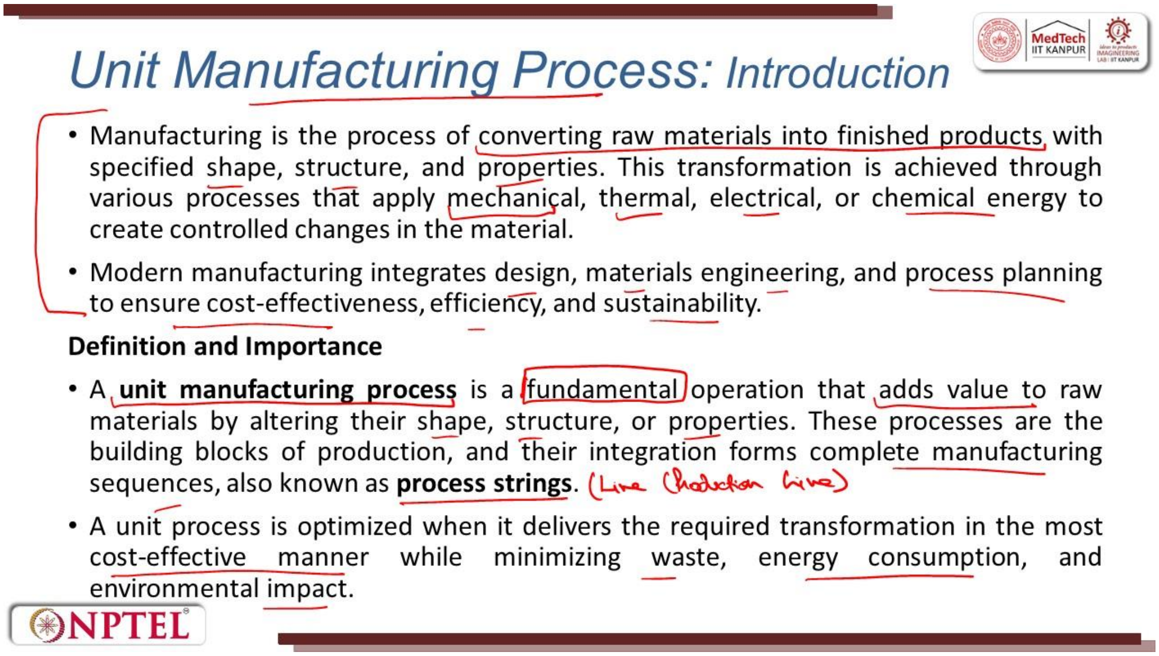
Now, collection and filtration. For example, when I talk about a big product like a car. When it is completely dismantled after the use phase, the nuts and bolts. The metal materials, such as aluminum, stainless steel, and other components, are segregated. That is collection and filtration.

Then, waste treatment material that cannot be used at all. That is waste. Going into disposal—that is waste treatment. This is useful for retrofitting but less effective than pollution prevention methods, as it manages rather than reduces waste. So, pollution prevention is the first priority.

Then, there is end-of-pipe control that we can do. Then, even if end-of-pipe control is somewhat restricted, we can at least have environmental restoration. Addressing environmental damage after waste releases through hazardous waste management. Site restoration, limited water and air treatment—costly and less effective, often a last resort when the system fails. For example, NASA, while launching a rocket, uses tons of gallons of water.

To restore it, they undertake certain endeavors for water treatment, water collection, etc. All those things are taken care of. Now, cost-effectiveness in comparison between the criteria and optimizing manufacturing through pollution prevention is very important. When I say cost-effectiveness, cost rises while effectiveness declines when shifting from pollution prevention to environmental restoration. Pollution prevention offers the best balance of cost and impact reduction.

Optimizing manufacturing through pollution prevention, focusing on pre-manufacturing stages, minimizes waste and emissions from the outset. Identifying and eliminating environmental impacts early makes it the most efficient and economical strategy. That is when we have eliminated them in the design phase, meaning we are primarily focusing on prevention only. Prevention is better than cure. This phrase always holds true.



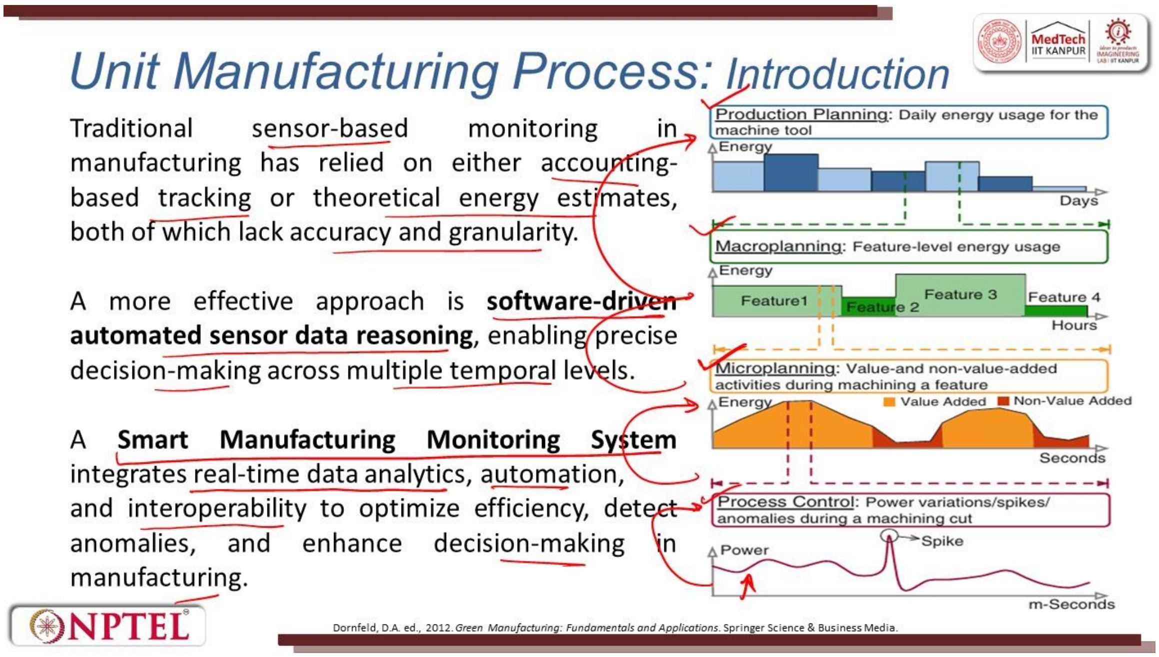

Let me now give a quick introduction to unit manufacturing processes. Manufacturing is a process of converting raw materials into finished products. Which we all know, with specified shapes, structures, and properties. This transformation is achieved through various processes that apply mechanical, thermal, electrical, or chemical energy to create controlled changes in the material. Modern manufacturing integrates designs, materials, engineering, and process planning to ensure cost-effectiveness, efficiency, and sustainability.

Why am I talking about manufacturing once again? Because when discussing manufacturing, we will talk about There are specific units, specific kinds of operations that we perform. For example, you are performing a turning operation. That is a machining operation. That comes as a unit process.

For example, if you are doing casting. In casting, you are specifically doing casting for a specific component. For example, you are doing casting for a carburetor for a car. For that casting is a unit manufacturing process. See, unit manufacturing process is a fundamental operation.

The word fundamental is very important here. It is a fundamental operation that adds value to raw materials by altering their shape, structure, properties. These processes are building blocks of production and their integration forms complete manufacturing sequences also known as process strings. This is also known as line or I will better call it as production line. Unit process is optimized when it delivers the required transformation in the most cost-effective manner.

While minimizing waste, energy consumption and environmental impact. So that is unit refraction process is the building block. If you try to work upon one block, if this saves energy. If this is replicated for each construction of a complete building. Then that building whole will be having the same equivalent percentage saving in the terms of any of the emissions, solid, water, etc. So to do this, we need to have certain sensor-based technology systems.




So traditional sensor-based monitoring system reflecting has relied on accounting-based tracking. And theoretical energy estimates, both of which lack accuracy and granularity. So nowadays, software-driven automated sensor data reasoning are there. Which enables precise decision-making across multiple temporal levels.

So you can see at a production planning level, at a macro planning level. Then micro-planning level and process control. From the process control itself, if I try to do something here. This will reflect up and finally production planning has to be done in such a way. A smart manufacturing monitoring system is one which integrates real-time data analytics, automation and interoperability to optimize efficiency, detect anomalies and enhance decision making in manufacturing.

## Unit Manufacturing Process: Examples

| Unit Process | Illustrative equipment | Workpiece material | Typical tooling | Typical Interface | Primary Workzone mechanism |
|---|---|---|---|---|---|
| Machining | lathe | bar stock | single Point | cutting Fluid | deformation, fracture |
| Surface Modification | furnace | part | atmosphere | diffusion | phase change |
| Casting | furnace | melt | mold | release agent | solidification |
| Forging | press | preform | die | lubricant | deformation |
| Powder Compaction | press | powder | die | lubricant consolidation | deformation |
| Fusion arc Welding | power supply | part | arc | plasma | phase change |

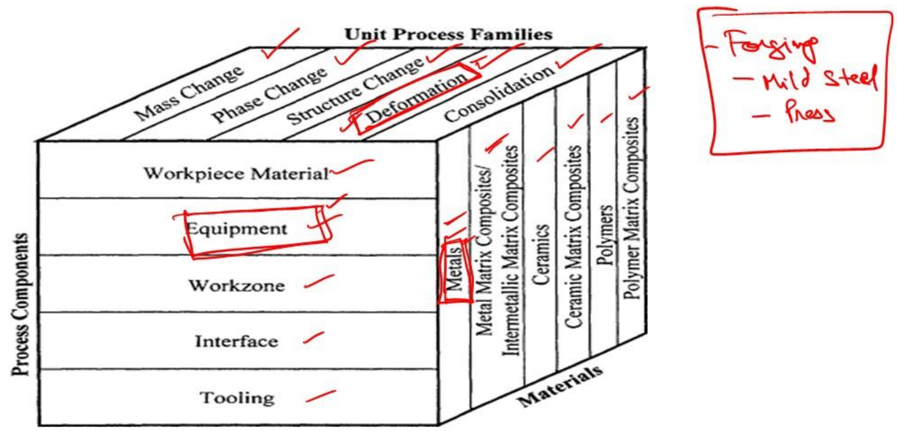
There are certain examples of unit manufacturing, as I took the example of machining. In machining, an example could be lathe, workpiece is bar material, type of tooling is single point. Typical interface across the tooling is cutting fluid, primary work zone mechanism is deformation and fracture.

Similarly, for other processes, which are unit processes, for surface modification, for casting, for forging, for powder compaction, for fusion arc welding. There are certain examples.

And let me take just one example of forging. The equipment is pressed. The workpiece material is preformed. The typical tooling is a die that converts it into the desired shape. The typical interface to the material is a lubricant.

And what is the primary work zone or mechanism here? It is deformation that occurs. So, there are certain examples of deformation. Unit manufacturing processes. These are all unit manufacturing processes given in the first column.

## Unit Manufacturing Process: Classification

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Now, unit manufacturing processes and process optimization. There are families of unit manufacturing processes. For example, there are unit manufacturing processes that work on mass change. Then phase change, structure change, deformation, consolidation. I will talk about all of these.

And these processes are further optimized. Based on the kind of material you're using, it could be metals, composites, or ceramics. Or maybe ceramic matrix composites, polymers, or polymer matrices as well. Then there are certain different process components that we are using. For example, workpiece material, equipment, works on interface, and tooling. So what specifically are we going to focus on when talking about our materials? Life cycle assessment goals can be picked out of these.

## Unit Manufacturing Process: Classification

Unit manufacturing processes can be categorized into five major families based on their physical transformation methods:

1. **Mass-Change Processes**: These processes add or remove material using mechanical, electrical, or chemical means, (Examples: machining, grinding, electrochemical machining).
2. **Phase-Change Processes**: These processes involve solidification from liquid or vapor phases (Examples: Casting, injection molding, metal infiltration).
3. **Structure-Change Processes**: These processes alter a material's microstructure to enhance mechanical properties (Examples: Heat treatment, surface hardening, annealing).
4. **Deformation Processes**: These processes change a material's shape without altering its mass or composition (Examples: Rolling, forging, deep drawing).
5. **Consolidation Processes**: These processes combine materials into a single component (Examples: Powder metallurgy, composite pressing, welding, brazing).

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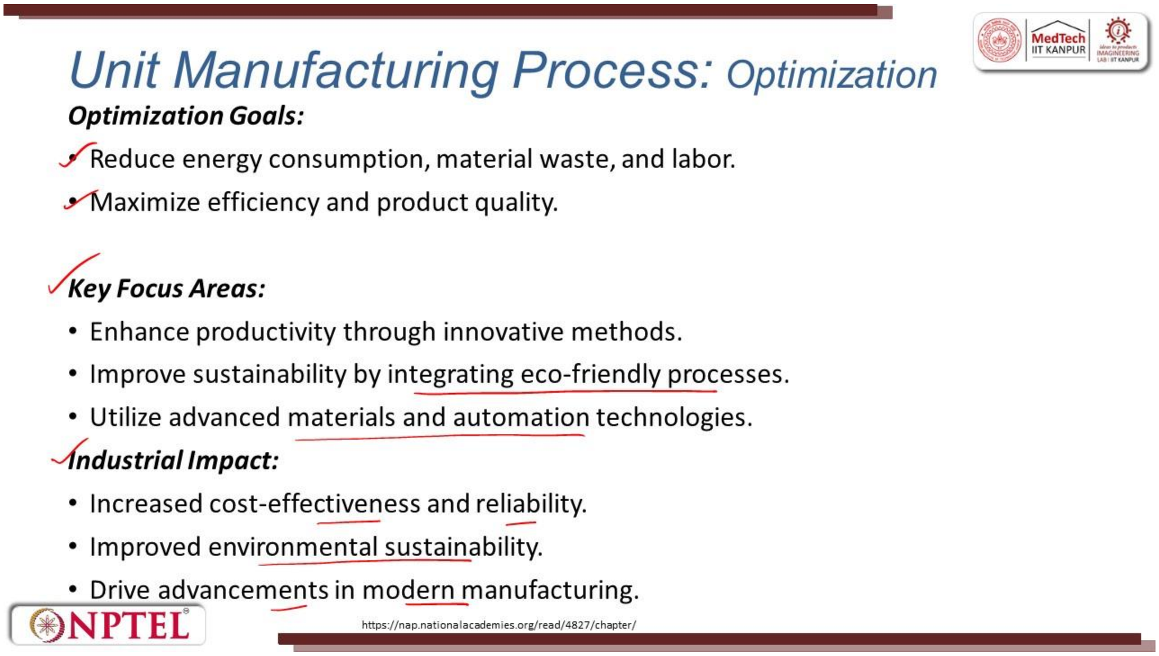
Now let me try to see the classification of unit manufacturing processes based on the families. Which I showed you in the previous illustration here. Unit manufacturing processes can be categorized into five major families based on their physical transformation methods.

Number one is mass change processes. These processes add or remove material. Using mechanical, electrical, or chemical means. Examples could be machining, grinding, electrochemical machining, etc. Then comes phase change.

When I say phase change, that means we will heat the metal above its critical temperature. So that is the process that involves solidification from liquid or vapor phases. For example, casting, injection molding, material infiltration. Then comes structure change processes only. When we alter the microstructure, that is the heat treatment process.

When we talk about those, they come under this structure change process. These processes alter material microstructure or enhance mechanical properties. For example, heat treatment, surface hardening, annealing, etc. Then comes deformation processes. As I have talked about, metal deformation happens.

Here we have material shape change without altering its mass or composition. That is rolling, forging, deep drawing, etc. Then comes consolidation processes. These processes combine materials into a single component. For example, powder metallurgy, composite pressing, welding, brazing.




Next comes during manufacturing processes optimization goals. That is to reduce energy consumption, material waste, and labor while maximizing efficiency and product quality. When I talk about green machining in the next chapter. I will also talk about the importance of optimization when I say optimization. You have to pick out of the range of materials available.

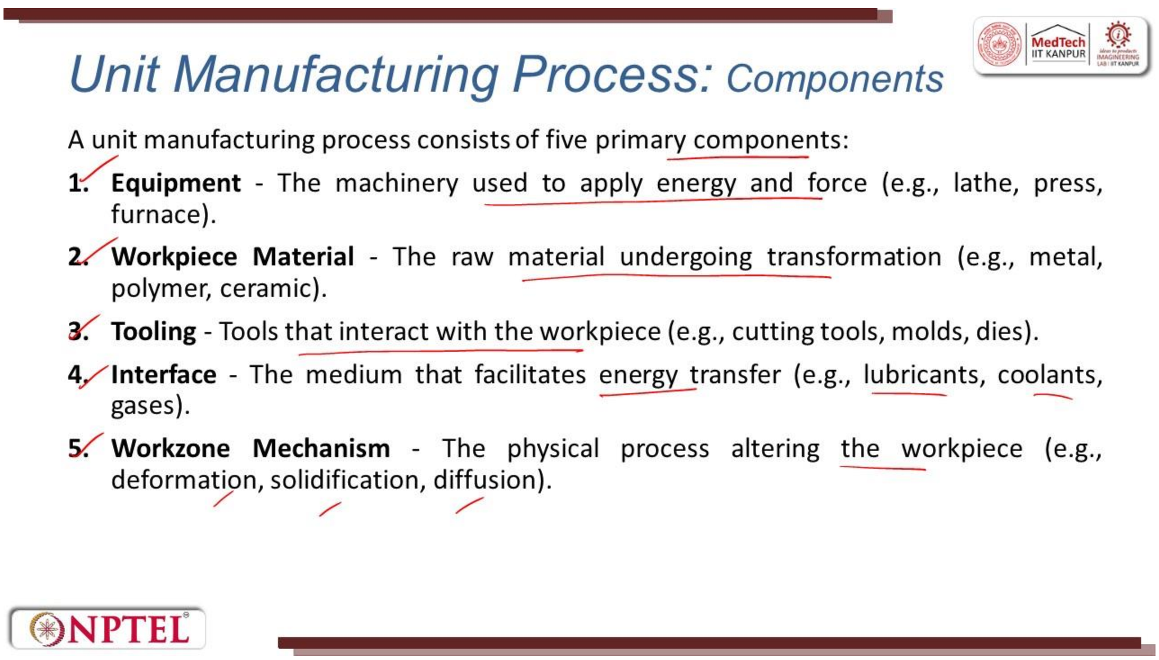
Out of the range of the different kinds of processes, out of the range of the different kinds of parameters in the overall system, what are we going to work on? That is, I am going to define my goal and scope of lifecycle assessment. For example, in this illustration, I have marked three different boxes here. You can say I have picked deformation, equipment, and metals. When I say deformation, that means out of all the unit process families, I will only pick deformation.

That is, I am talking about forging, right? Then, forging of only metals. For example, I will talk about forging of mild steel. Then, when I am talking about deformation and metals deformation out of the workpiece. Material work zone interface, what I'm going to focus on is the forging equipment.

I'll talk about forging press. This is me defining my goal or scope of the life cycle assessment, where I'm trying to pick a specific kind of equipment from the deformation family. And I'm going to pick materials that are metals only, with the process being equipment here. I have to pick those which significantly affect my overall product life cycle. Equipment energy, energy used in work material, energy used in the work zone.

Equipment will occupy maximum energy. If I am trying to focus on energy, I might pick these. I might pick some others depending on the scope of my study. So this is what we will try to work on for optimization. The key focus areas of optimization are enhancing productivity through innovative methods.

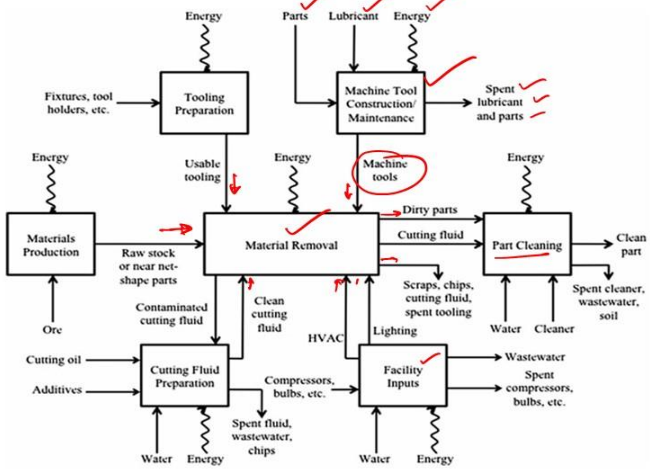
Improving sustainability by integrating eco-friendly processes, utilizing advanced materials and automation technologies. The industrial impact of optimization includes increased cost-effectiveness and reliability, and improved environmental sustainability. It drives advancements in modern manufacturing.




Again, talking about the five primary components: equipment. The machinery used to apply energy and force, workpiece material. The raw material undergoing transformation, tooling, tools that interact with the workpiece, and interface. The medium that facilitates energy transfer could be lubricants, coolants, etc.

And the work zone mechanism, which is the physical process altering the workpiece. That could be deformation, solidification, diffusion, or anything like this.

## Unit Manufacturing Process: Boundaries




Dornfeld, D.A. ed., 2012. *Green Manufacturing: Fundamentals and Applications*. Springer Science & Business Media.

## Unit Manufacturing Process: Boundaries

**1. Raw Material Extraction & Preparation**
- Inputs: Ore, Raw Stock, Near Net-Shape Parts
- Processes: Materials Production
- Outputs: Usable Tooling, Processed Material

**2. Tooling & Machine Preparation**
- Inputs: Tooling, Fixtures, Tool Holders
- Processes: Tooling Preparation, Machine Tool Construction & Maintenance
- Outputs: Ready-to-Use Machine Tools

**3. Cutting Fluid Preparation**
- Inputs: Water, Additives, Cutting Oil
- Processes: Cutting Fluid Preparation
- Outputs: Clean Cutting Fluid

Now, let me try to see the boundaries of a unit perfecting process. When you talk about a uniform effecting process, if I am talking about supposedly. Only machining—machining is typically material removal in material removal. There are certain boundaries in material removal. We have associated boundaries. We have material production that comes as input, tooling preparation, single-point cutting tool.

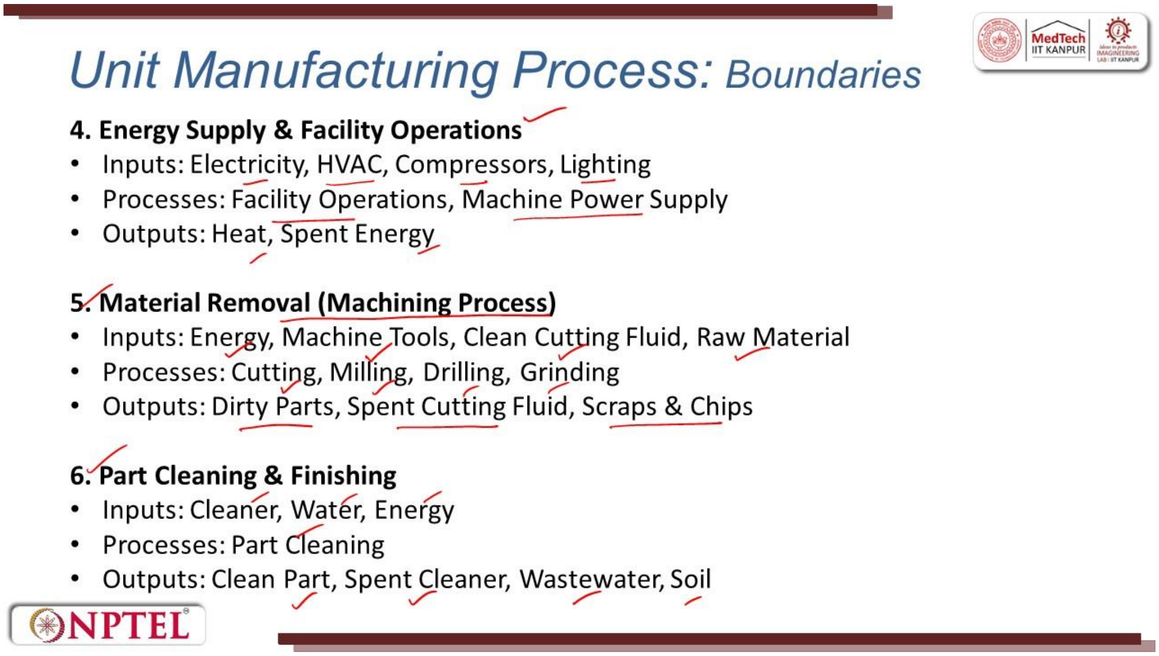
Or any multi-edge cutting tool that comes for the material removal. Then we have machine tools that come into interaction. Then we have cutting fluid that goes inside and outside. And I will talk about the methods such as minimum quantity lubrication. The only input is here.

There is no recycling of cutting fluid here. Then we have facility inputs that are lighting, heating, ventilation heating systems, or such that come here. Then comes part cleaning. That is, dirty parts go out and cutting fluids go out. So here we have the scrap or the emissions here.

These further each of them have their own interactions. For example, if I only talk about the machine tool. The machine tool has in itself the parts of the machine tool, the lubricant of the machine tool. The energy that is being consumed in the machine tool is variable. They spend lubricants and parts.

So these are all interactions or the boundaries of a specific kind of unit perfection process. If you try to focus upon, let me try to see each of the boundary boxes one by one. Raw material extraction and preparation. Inputs could be ore, raw stock, near-net-shape parts. Processes could be material production.

Outputs are usable tooling and processed materials. Tooling and machine preparation. Inputs are tooling, fixtures, and tool holders. Processes are tooling preparation, machine tool construction, and maintenance. Outputs are ready-to-use machine tools. Cutting fluid preparation. Inputs are water, additives, and cutting oil. Processes are cutting fluid preparation. Output here is clean cutting fluid.




Energy supply and facility operations inputs: electricity, heating, venting, air conditioning, compressors, and lighting. I am talking about a facility that is a specific facility now. Processes are facility operations and machine power supply; outputs are heat and spent energy. Material removal is the core machining process.

Here we have inputs as energy, machine tools, and clean cutting fluid. Raw material processes could be cutting, milling, drilling, or grinding; outputs are the dirty parts, spent cutting fluid, and scraps. And chips part cleaning and finishing inputs are cleaner water and energy processes are part cleaning. We get as an output clean parts spent cleaner waste water and soil.

Next and the last is waste management and recycling. In this, the inputs are spent lubricant, contaminated leak cutting fluid, scraps and chips. Processes are waste treatment, recycling, reuse of materials.

This is very important here. Outputs are recycled material, properly disposed waste. Sustainability and green manufacturing considerations just to summarize. Have to focus upon energy efficiency, that is reduce energy consumption in machines and heat emitting air systems. Then waste reduction, recycling and reusing spent fluids and metal chips.

Then process optimization that is minimizing raw material waste by adopting near net shape manufacturing and eco-friendly coolants. And lubricants using bio-based or recycled cutting fluids. I will try to focus or talk about these in the next lecture.

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When I will talk about green machining and there are certain references from which all this material is taken. With this I am closing this lecture. In the next lecture, I will talk about green machining, and in the last lecture of this week, or in this course, I will talk about certain metrics of sustainability.

Thank you.