Metal Additive Manufacturing
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Lecture-38
Sustainability in MAM (Part 1 of 3)

Welcome to the course on Metal Additive Manufacturing. In this lecture, I am going to talk about Sustainability in Metal Additive Manufacturing. Sustainability is the concept, that entails meeting the needs of the present generation without compromising the needs of the future generation; that is limiting the resources or minimizing the use of natural resources. When I say natural resources, it might come in the form of material, it might come in the form of energy and also trying to use the non-renewable sources wherever possible.

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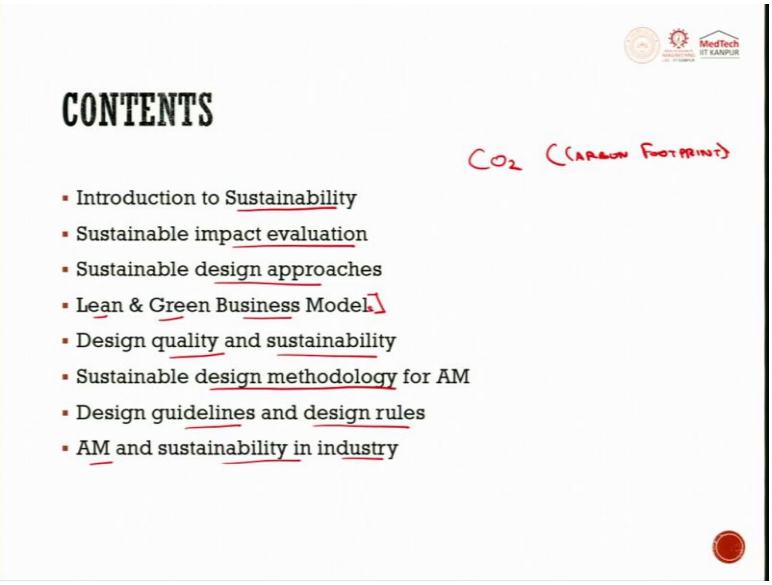

When we talk about additive manufacturing, sustainability in itself is one of the goals of additive manufacturing because additive manufacturing reduces the excess material, the ability to use a generative design also plays an important role in terms of part optimization. And because of the generative design, the material that is used in the inner body of the part is reduced. So, that is one of the advantages of metal 3D printing in comparison to traditional manufacturing methods.

The 3D printers also enable on demand manufacturing, so this is not only to save time, but also it eliminates the need of the long transport routes, the storage area, the consequence reducing carbon footprints. When I say carbon footprints, that is the amount of carbon

dioxide that is produced. This is carbon footprint. So, please mind this word when I say carbon footprint, it is generally the amount of the carbon dioxide.

Now, this course would have an introduction to what is sustainability as a concept, sustainable impact evaluation, how is that conducted in sustainable design approaches, Lean and Green Business Models, when I say business models, it involves green manufacturing systems and additive manufacturing systems, specifically focusing on the metal additive manufacturing.

So, there are direct and indirect affects always of Additive Manufacturing, all of them to be taken into account, for example, the pollutants which are produced, reduction of pollution is one of the immediate and the long-term goal always in green manufacturing, but sometimes internal pollution is always there, like when we try to use a printer in the laboratory.

There are small dust particles, which are also to be taken into account, that what is the size of the dust particles. Dust particles means the particles coming out of the fused deposition modeling method or the powder if it is coming into the air in the sizes of the microns or nano level. So, it might come out and these are also detrimental to the health of the worker and in future. Overall, detrimental factors are there.

So, all these things in the business model are to be taken care that design quality and sustainability, how do we have the tradeoffs between them. Sustainable design methodology, there are general approaches accepted by the major sustainable or green manufacturing gurus. We will try to pick a few of them and try to see, what is the general procedure to have a sustainable and manufacturing system.

Then, design guidelines and design rules to implement or to employ the sustainable methodologies. Then, additive manufacturing and sustainability in industries: What kind of materials are there? What energy they use? Production of powders? What materials should be selected? What materials are having or consuming higher energy? Which processes are consuming higher energy or the materials? Which are not biodegradable?

In general, because we only talk about metals here, there are hybrid material always which can also be used. Hybrid materials, the mix of the metal materials and the biodegradable materials. But in this lecture, we will more focused on the sustainable methodology, the sustainable technologies, why do we need sustainability. So, 1 or 2 models we will discuss.

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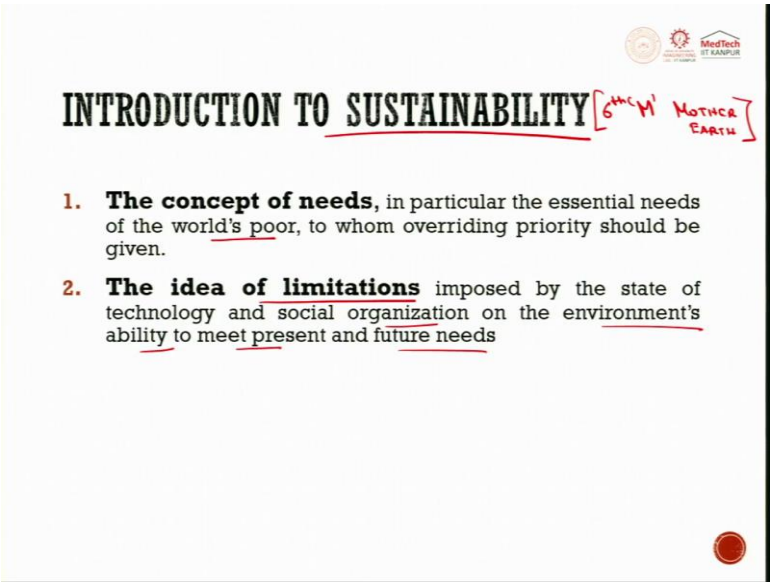

So, let us have a quick look on what is sustainability? The concept of needs in particular essential needs of the world's poor, to whom overriding priority should be given. The idea of limitations that is the resources that we have right now. Whatever is available on the earth we call it Mother Earth. There are 5Ms in manufacturing, man, material, money, management, marketing. There is now 6M that is known as M that is Mother Earth.

This is the sixth M of the management whenever the things are now designed. So, the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs. So, there are certain pillars of sustainability, that we will discuss in the forthcoming slides.

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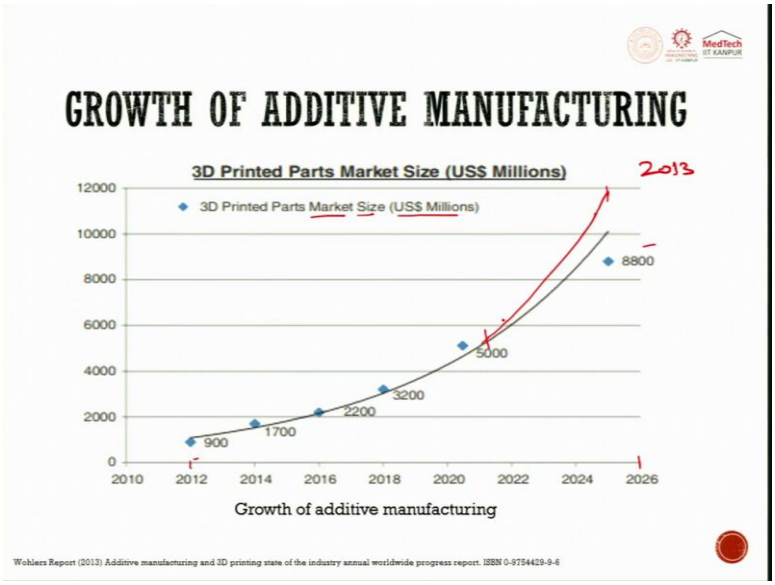

So, growth of additive manufacturing systems, if you see this graph given by Wohlers that the growth of additive manufacturing has gone from 2012 to 2026 and it is around 10-fold of the growth. So, these are the 3D printed parts manufactured and the market size in the US billion dollars. So, you can see, it has risen from around 900 million dollars to around 9000 million dollars in the span of 12 years.

So, right now, we are around here and the way the graph is going, it could even go more steep further so, the graph could also be having bigger size based upon the way that technologies have been developed. This report was created in 2013 only. So, now, the way the technologies have taken this have definitely taken a steeper growth now.

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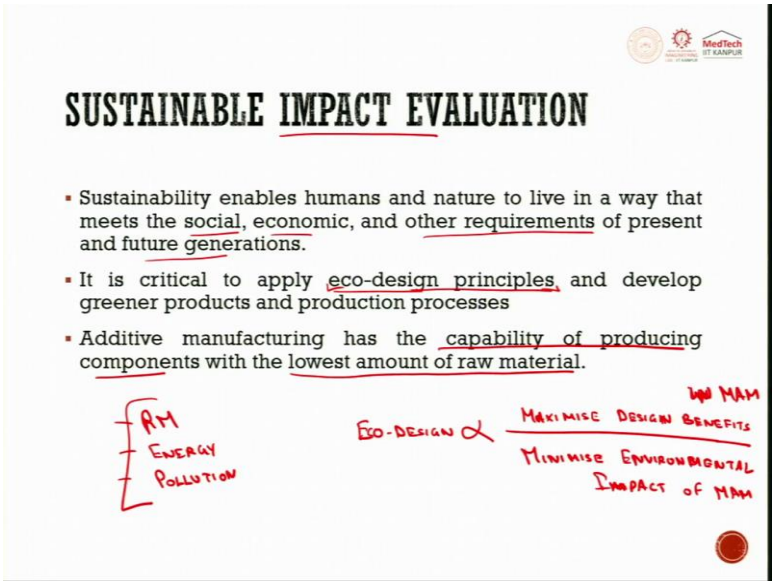

So, this is just to understand the impact evaluation of sustainability. Sustainability enables humans and nature to live in a way that meets the social, economic and other requirements of present and future generations. It is critical to apply eco-design principles. So, what is an eco-design? Eco-design means we try to minimize the environmental impact and tries to maximize the design benefits. We will try to discuss that as well.

I will put it here, eco-design this is proportional to maximize designed benefits and minimize environmental impact. Environmental impact of additive manufacturing or metal additive manufacturing as per this course, maximum design benefits in or of metal additive manufacturing. So, the aim of eco-design is to maximize design benefits and to minimize the environmental impact of it.

So, environmental and social concerns about human society's impact on the natural environment have been pushing the sustainable development issues all the time. Now, sustainable industrial practices can contribute to the development of more sustainable materials, more sustainable products, greener processes and so on.

Now, additive manufacturing has the capability of producing components with the lowest amount of raw material. We will talk about raw material; we will talk about energy and somewhat also we will touch pollution that these are the major factors that contribute to the environment or that are the indicators of the sustainable design. So, raw material energy and

pollution being the major factors or the indicators that determine the sustainable index of a product or of a process.

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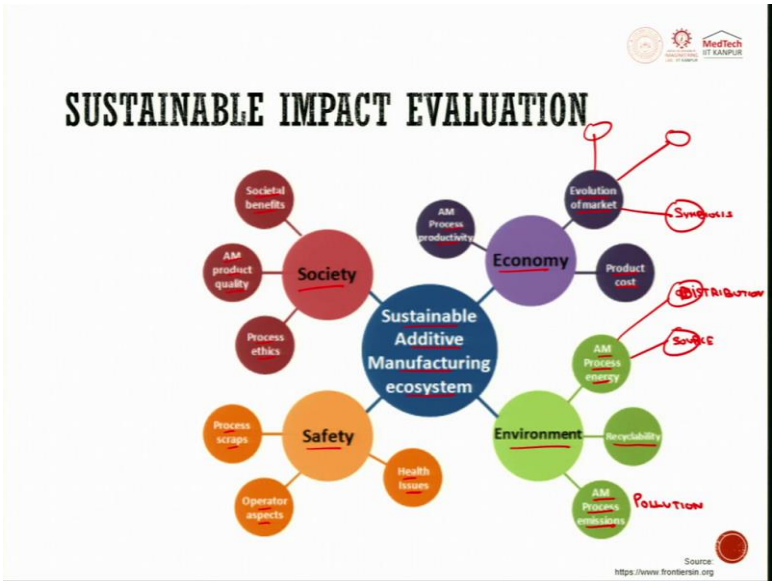

Majorly society, economy, environment and safety are the foundations based upon which sustainable additive manufacturing ecosystem is designed. So, in economy, additive manufacturing process productivity has to be taken care of evolution of the market and as per the market demand, how the economy, how the funding, how the finances are there, cost of the product is taken into account.

Then, we have society, societal benefits, that is the immediate effects on the worker's health. The long-term effects while using the energy that is produced from the resources which are in itself more detrimental to the environment, for example, the energy that is produced from coal. So, that is the thermal power plants we will discuss about the lifecycle impact analysis, this will be detailed.

Then, additive manufacturing product, quality, process, ethics then safety is also one of the concerns, process crabs, operator aspects, health issues. In the environmental viewpoint additive manufacturing process energy recyclability of the products that you have, we have we are using. We will try to see what is a circular economy, what is the reusing, recycling and additive manufacturing process emissions, that is the pollution, these play an important role.

These are the sub-factors, so these factors also might have certain different nods with them. Evolution of market could be, industrial symbiosis. Then, we can have in the process energy as I just talked about, whether the energy is coming from what kind of the source, what kind of energy generation source is there.

Then, in the process energy also it could be the optimization of the energy distribution, I will put a distribution so, the connecting factors could be further added in the making, the whole chain, the whole tree of the factors.

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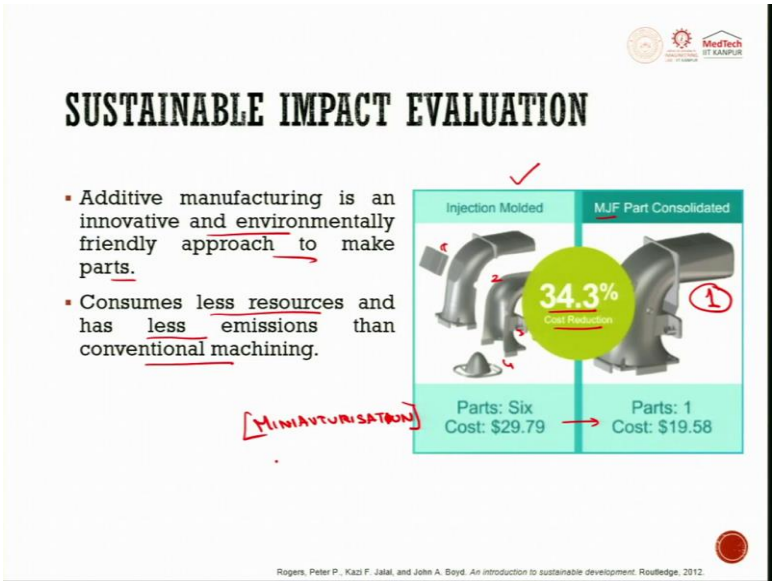

Sustainable impact evaluation to pick an example here, additive manufacturing is an innovative and environmentally friendly approach to make parts. It consumes less resources and has less emissions than conventional machining. So, in the injection molding part or injection molded part you can see 1 2 3 4 components were there. It had 34.3 percent cost reduction this is an example taken from the reference.

So, the part cost is reduced and using the multi jet fusion part consolidation process a single part is produced. This is the benefit or this is advantage of additive manufacturing. In metal additive manufacturing sometimes, there are special components or special parts to be produced and only single parts is to be produced as we discussed in the reverse engineering.

We try to reverse engineer that and if the original equipment manufacturers do not have that component available and it is broken in the machine, those could be reproduced in place of getting the machine or the overall assembly replaced, a single component could be replaced.

This also contribute to the sustainability. Now, this concept is known as miniaturization. This small component could also be produced or having the component produced in modules.

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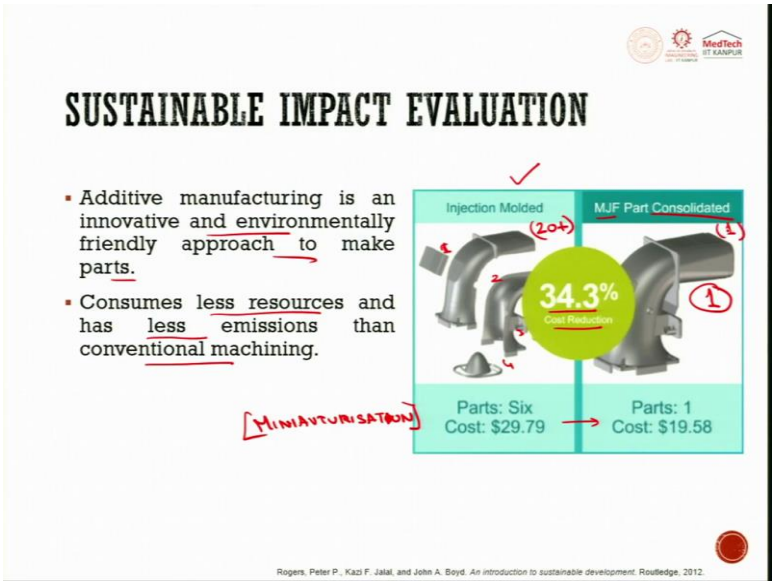

Now, environmental sustainability in additive manufacturing machines are tiny and may be situated near any market and it decreases the logistics of transferring products to any part of the world. So, supply chain efficiency is always there, that is the complex parts which enables less waiting are also produced here. Reducing the need of mine and process natural ores and replacing energy inefficient and wasteful manufacturing techniques like casting, CNC machining and so on.

So, in customization the part could be customized to the specific component it could be reverse engineered or it could be reproduced or single component could also be produced. So, if you have a particular customer, the physical space or application, it could also all be taken

care of. Consolidation, that is reducing the number of sub components as we saw in the previous example.

Though this is consolidation part only. And intermediate operations are also reduced here. In conventional machining, part 1, 2, 3, 4 each of them would have its own operation. So, there are multiple intermediate to patients. So maybe to produce this component using conventional machining. It could have employed 20 plus operations. In this we are able to do it in a single operation.

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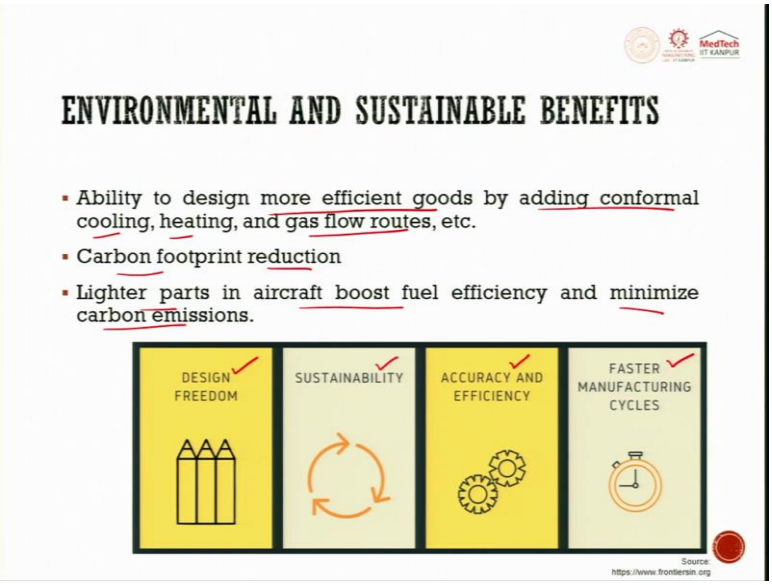

Now, environmental and sustainable benefits, it allows us all to design more efficient goods by adding conformal cooling, heating, gas flow routes, etc. carbon footprint reduction is there, lighter parts in an aircraft boost, fuel efficiency and minimize the carbon emissions.

So, we have design freedom, we have sustainability benefits, accuracy and efficiency is also competent to the traditional manufacturing or it at certain points it is better and faster manufacturing cycles are there. So, there are all always some pros and cons of all the processes that we do.

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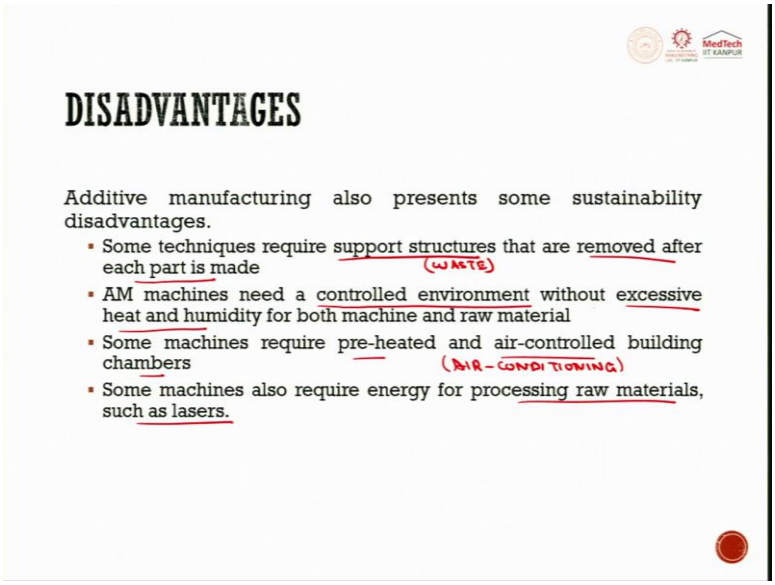

So, there are small disadvantages like additive instruction also presents some sustainable disadvantages, Some, techniques require support structures that are removed after each part is made that this goes as waste. So, additive manufacturing machines need a controlled environment without excessive heat and humidity for both machine and raw material. Some machines also require pre-heated and air-controlled building chambers.

So, that means, air conditioning so, the buildings are to be designed in such a way so, the workplace or the factory design that is made for additive manufacturing niche to have these conditions. So, this also becomes a lurking variable that is not directly affecting, what is the overall input of the factory, the energy input of the factory sometimes also is more when we try to employ additive manufacturing wholly.

So, some machines also require energy for processing raw materials such as lasers etc. So, there are all always the ups and downs or there are always the pros and cons.

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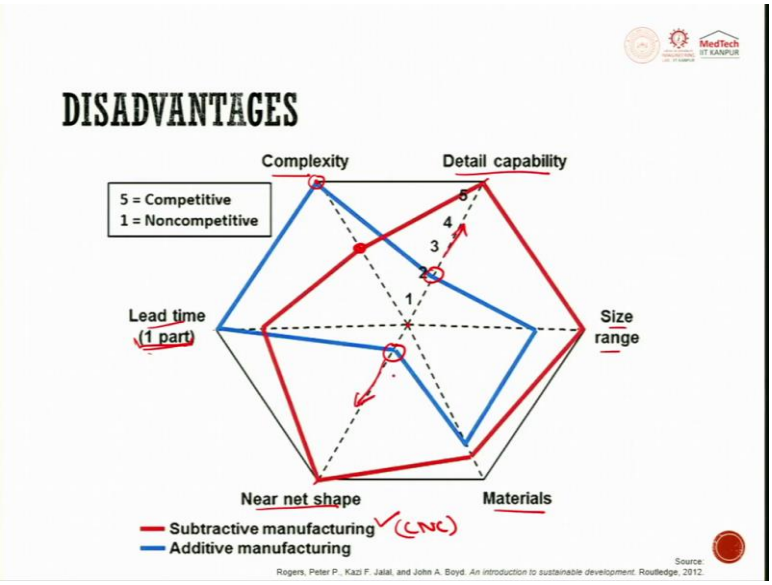

So, if we tried to compare in the terms of complexity, detail capability, size range, material and near net shape and lead time. This is a web diagram in which the central point shows the non-competitive and towards the edges we go the competitive so, that means, the more the process is towards the edge or more the factory is towards the edge, more it is better.

That means more the factor any of these factor's complexity, capability, size range is towards the edges of this web, that is in a hexagonal web. So, more it is competitive that is it is better. Now, size range that is available in the subtractive manufacturing which generally I put here CNC manufacturing for the subtractive manufacturing and detail capabilities also there.

And net near shape is also produced using the CNC manufacturing, which we are using for decades. Now, additive manufacturing has benefits over lead time, that is single part if it is to be developed. For a single part the lead time reduces and the need of the design of the complex parts, in this the complex parts in subtractive manufacturing we need to have these specific setups, we need to have specific fixtures for designing or for to manufacturing component, if it is as is to be redesigned.

In the additive manufacturing it is just allows us to re-engineer it that is reverse engineer it and try to produce any of the complex components. So, these are a few comparisons. Now near net shape and detail capability are few of the drawbacks that still are there in additive manufacturing but this was also a plot that was made years back now, we have improved these processes or these factors as well.

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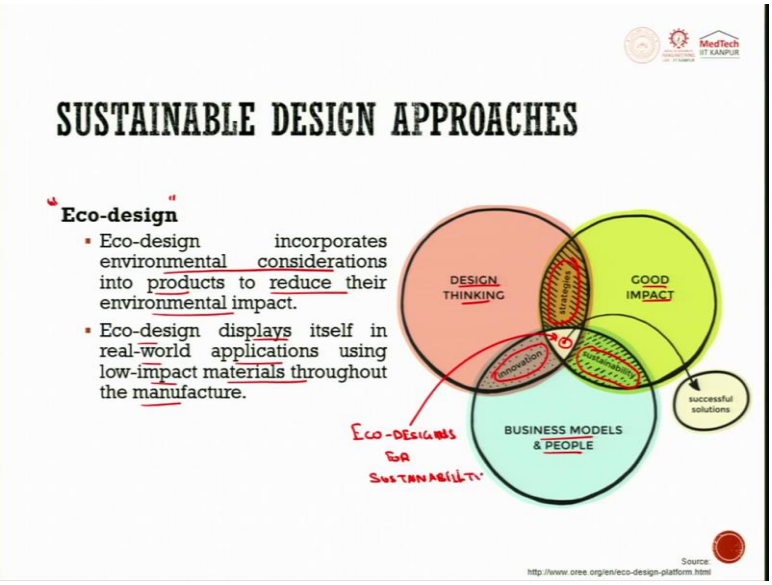

Now, eco-design. Eco-design as I mentioned, it tends to maximize the benefits in the design and tries to minimize the environmental impact. So, this incorporates environmental considerations into products to reduce the environmental impact. Eco-design display itself in a real-world application using low impact material throughout the manufacture. So, design thinking, good impact, make your strategies to be at par of eco-design.

Then, business models and people with design thinking helps to have innovative designs and good impact, that is the environmental impact, that is better than before and business models and people helps us to have sustainable manufacturing. So, these are the successful solutions that we get here at the center. So, I will call it these designs are the eco-designs, eco-designs for sustainability.

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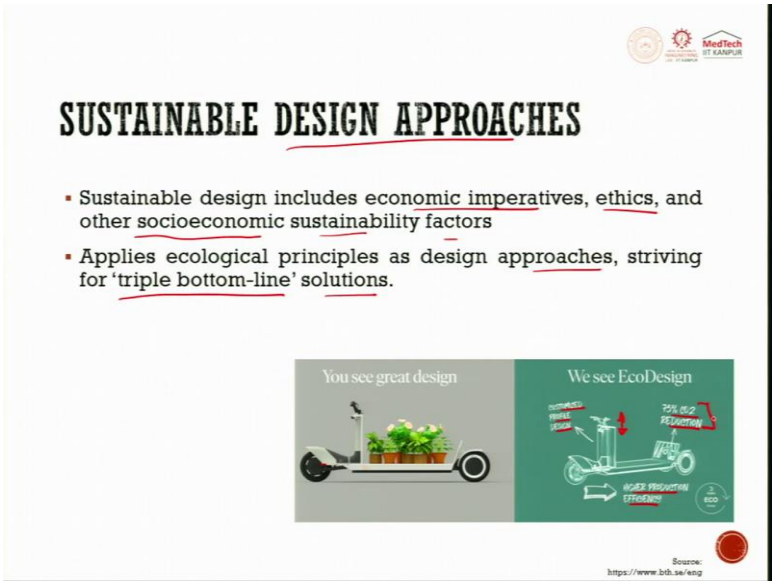

Having a look at the sustainable design approaches. The sustainable design includes economic imperatives, ethics and other socio-economic sustainability factors. This now we apply ecological principles as design approaches striving for triple bottom-line solutions. Once, a customer sees a product as a great design, color and so, an engineer sees it as a customized profile design, the handle is customized so as it could be adjusted up and down.

Then, the engineer also thinks or the sustainable engineer thinks that it has to have high production efficiency, it has to have the reduction in the carbon footprint because it is not using any fuel it is an electric vehicle. There is always a tradeoff electric car and the fuel cars, it is said that the American Fleet by 2030 would have more than 40 percent of the electric cars. But still this is a matter of discussion, rather how to dispose of the batteries, how many battery recharge junctions would we have definitely infrastructure will be employed for that.

So, what is the investment in the terms of the manufacturing of the or the construction of the battery charge, battery recharge junctions and the overall system then, how to dispose of the battery, the legend the battery, where to dispose of as a solid waste, these all calculations are still going on. How do we because always battery though, is rechargeable, it could be used time and again, but at some point, of time, it disposes of calculating that environmental impact and environmental impact using the fuel, the battery system still has an edge over it.

So, that is why battery systems are being employed. So, this has 75 percent of the cost reduction using a battery system.

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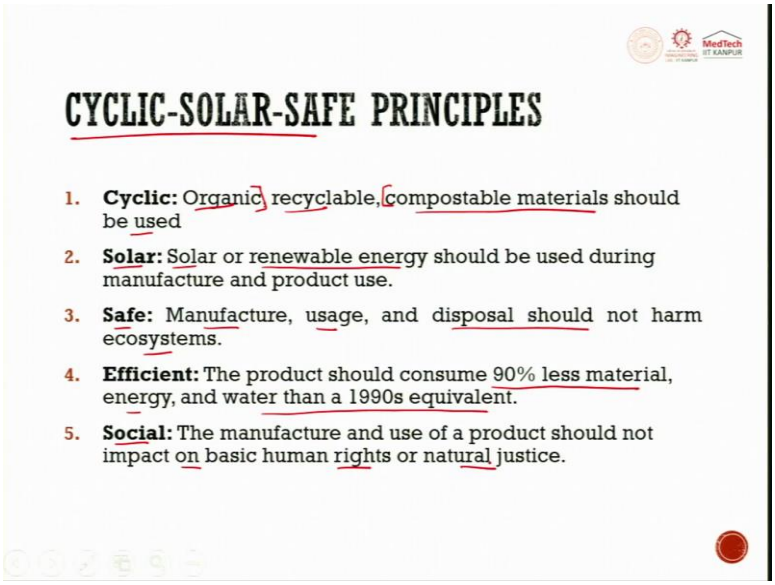

This is something known as cyclic solar safe principles, CSS principles. Cyclic means organic, recyclable, compostable materials should be used. These are the general sustainability principles, that we are talking about. Metals could be recycled, they are not organic, definitely those do not come but in hybrid materials, this could be used.

Compostable materials or also could be used in the hybrid in the composite metal manufacturing systems as well. Solar means, its renewable source of energy could be used, at least it raises a building like I said, we can design a facility that has to be air conditioned. Air conditioning generally could not be taken care by solar, but general lighting system can definitely have solar charging.

Then safe, that is manufacture, usage and disposal should not harm the ecosystems. Efficient systems, the products should not consume 90 percent less material, energy, and water than 1990s equivalent. So, we have to think of though the consumption patterns are going high, the consumer is demanding more and more products, the consumer is able to spend more on the concepts, but these 5 sustainable design components are the principles that mimics the plant or an animal ecosystem and tries to say how it could be eco efficient.

Now, the fifth system is the social. The social principle says the manufacture and use of a product should not impact on the basic human rights or natural justice.

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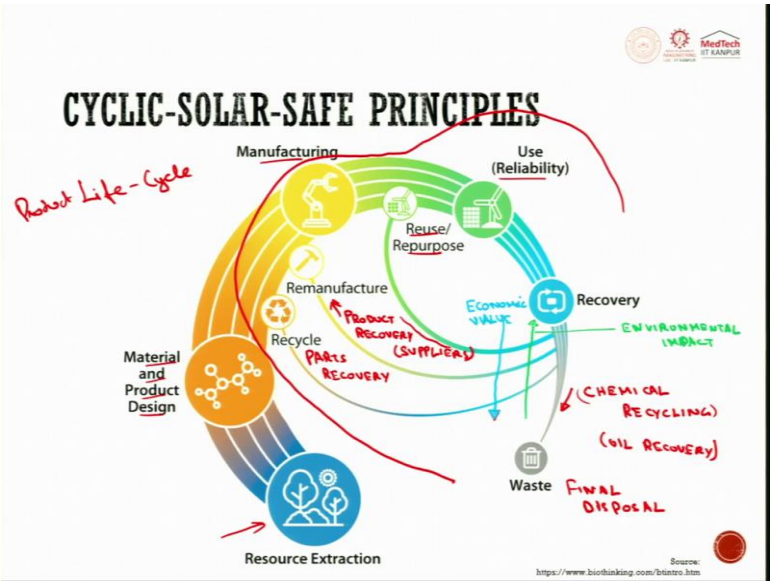

So, if I try to plot the CSS system, cyclic solar safe system, this is something known as the circular system in which the resource is extracted, the material and product goes as a design and when manufacturing happens. Here, come the use and reliability after the use the recovery could happen in multiple phases or multiple ways. First is, the reuse of the component.

The powders which are collected in the Powder Bed Fusion, it is reused, reuse of the powder, repurpose. Now, remanufacture some of the components for example, the additive manufacturing if it is having an assembly of 2 or 3 components, 1 component goes wrong that could be put as a module there. So modular design in the topology optimization, the modular design is also there.

So, remanufacture, recycle is always the third option. When we try to completely melt the component and we try to recover the material the past recovery happens here. So, it is the past recovery I would put it here. In remanufacture, we try to take control of the part, we try to just reuse them. So, it is product recovery.

Reuse is nothing but using the product time and again. For example, you get your bike serviced time and again and keep on using it for 5 years or 10 years, you get your car serviced. You get your mobile phone if 1 component goes wrong, you try to get it manufactured, guide plate had to get repaired and maintained time and again, that is reusing.

Now, latest age it comes, it goes to waste, that is that has to be the last stage, but it goes to the waste. So, this is parts recovery, the recycling is parts of recovery. So, this is the when it goes to the waste, again, we have chemical recycling here. Then, we have oil recovery. Finally, when nothing is left over, when the suppliers are not able to do much in the product recovery, they supply the spare parts as well. I will put suppliers or the stakeholders here.

So, when the thing is left over, everything now goes to the final disposal. This is the final disposal that we get. If I see the use cycle here, this is actually the overall product lifecycle, starting from the extraction of the ore to the waste so, this is life cycle, we will talk about this or product lifecycle. In the coming slides, we will talk about this.

See, if I see this in a unison or in isolation, the reuse, and recovery and demon fracture or better I would use the remanufacture part as well. If I try to use this part when manufacturing and recycling everything, when I go towards keep on reusing and remanufacturing right from here to here, when reusing it I am going down, this is the economic value, let me try to use a different color.

Now, if I am trying to come down here the economic value or the product, overall value is reducing. Economic value is reducing. But if we keep on reusing it, taking the green color, I will have to put it here that if we keep on reusing it for more number of time, then, only go for remanufacturing then, only go for recycling. Then we have the environmental impact, this is environmental impact that is higher on the upper side.

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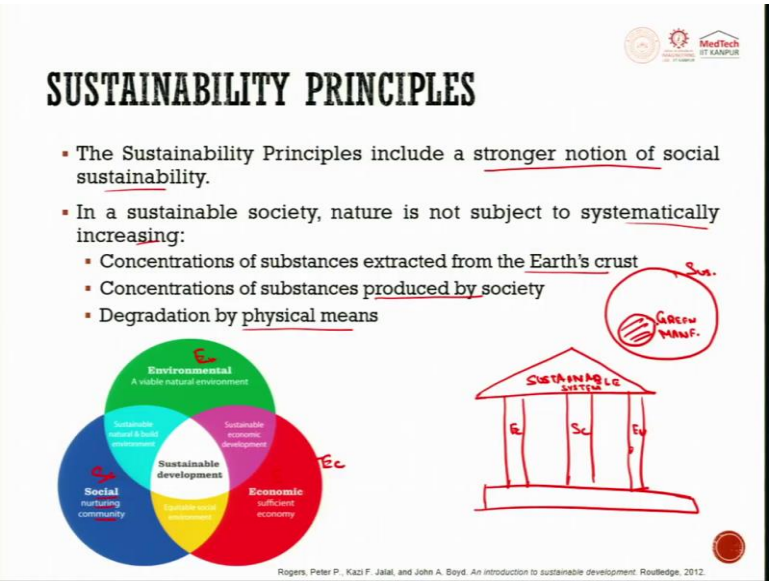

So, talking about sustainability principles. So, these include a stronger notion of social sustainability, to talk about sustainability as an overall concept, society or social nurturing community is always one of the factors. In a sustainable society, nature is not subject to systematically increasing that is the concentration of substances extracted from the earth's crust. Then, the concentration of substances produced by society.

Degradation by physical means. So, that is why something that we just mentioned in the previous slides, triple bottom line, that is, there is not a single bottom line all these 3 factors, these actually act as the pillars to hold the building of sustainability. If we have sustainable system, it has 3 pillars 1, 2, 3. I will put E for environment S for society and EC for economy, EV for environment, SC for society.

So, it has economic that is EC, then, it has society as SC and environment. This is known as a triple bottom line that provides that all the principles to hold the sustainability. Now, what we are talking about in sustainability as a system, is something known as green manufacturing. If sustainability is a bigger concept for society and everything takes care of, this is sustainability. We have a subset of it that is known as green manufacturing.

This green manufacturing becomes a subset of sustainability. Sustainability, however, considers everything in society that is the domestic use of the product, the total lifecycle, impact of the product, the societal benefits, and the society how does it behave to the product. Green manufacturing, what it takes about the manufacturing viewpoint as a manufacturer, as an engineer and or within a manufacturing system.

Here, in the terms of the metal manufacturing systems. In manufacturing, what powders do we choose, what energy system do we use, how do we control the pollutions? In only the manufacturing, these systems work.

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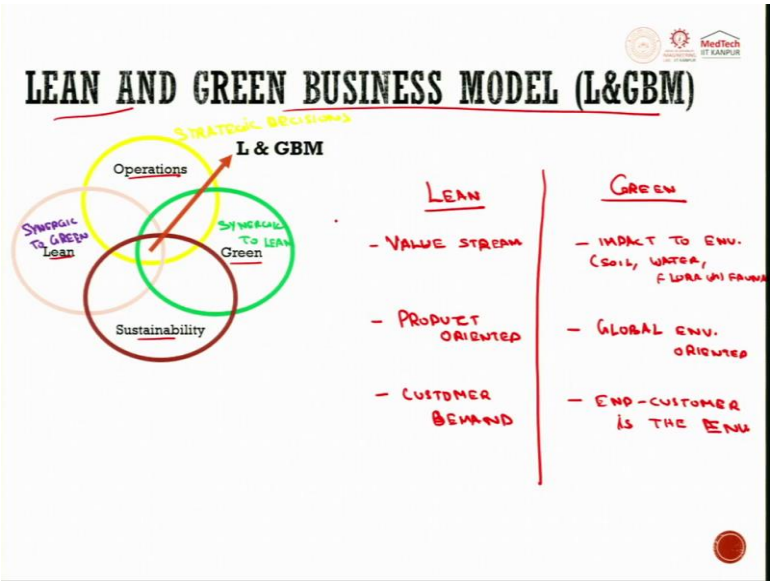

So, there is something known as concept, lean and green business model, L&G business model given by Pampanelli, so, it says that operations, lean sustainability and green all of them create lean and green business models. So, they say in operations, one needs to have strategic decisions, in the terms of the lean, lean means, the minimum amount of the waste and minimum amount of the resources as far as possible.

So, lean says, lean is way to green, it is integration of lean and green and introduces new dimension to the lean. So, this Lean is synergic, synergic to green. Similarly, green is synergic to lean. Sustainability gives the practices, which are capable of producing sustainable dimensions. So, lean supports people and profit, sustainability supports the environment people and economy all of these.

So, lean and green business model what does it in detail tries to tell us that first to put a delineation between lean and green how do they differ. When I say lean manufacturing and green manufacturing, it looks like lean is cleaner? Lean is cleaner in terms of putting the resources in the way that no wastage is here, for example, we can say the person could have lean physique that is there is no fat at all.

Your wardrobe could have lean setup, a clean set of the clothes, that is no extra clothes that you do not use for years or for months that is not there, that is lean. Green means the clothing that we are using, is using a material that is having natural fiber, that does not have any synthetic material or so, this could also one of the factors. So, green is a bigger factor, but lean definitely leads to green.

So, to provide a little difference between them, how do we put them together. Lean is synergistic with green it is already written. It focuses on the value stream that what value this specific process offers value stream analysis and is this value really required or not? So, this is value stream at the green sights the surroundings of impact, it is the impact to environmental, impact environment that is what is the amount of or how does it affect the soil or groundwater or maybe the ecosystem that is flora or fauna.

Now, lean is product oriented, that the product that we need to produce has to have lesser number of parts, then the cost is reduced. Green is the global event, environment-oriented. Lean is focused on the customer demand, what does customer need, it was the concept design, that what is the customer demand and just based upon the customer demand it designs customer base need.

The function-based. What is the function that customer require, customer requires something that should look good, it required something that should be comfortable for wearing? So, that is how it is designed for in terms of the products. Now, green says the environment is a customer. It says our end customer is environment. So, how does this model go about?

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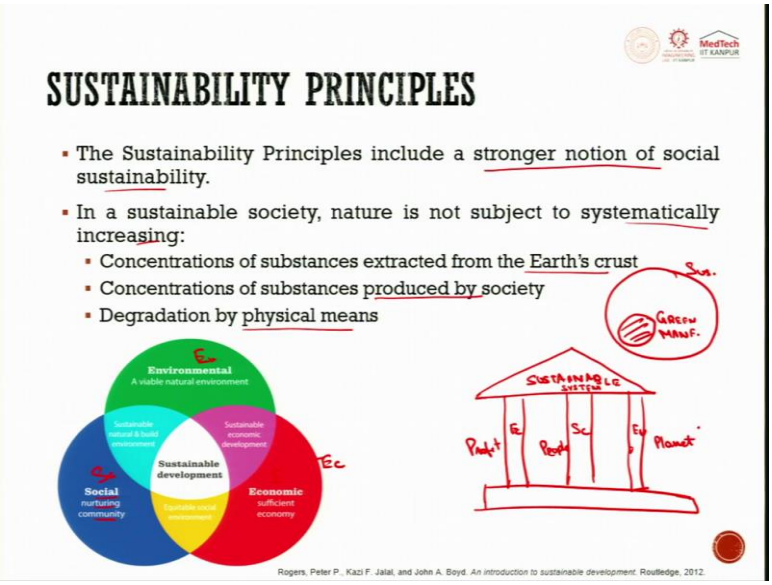

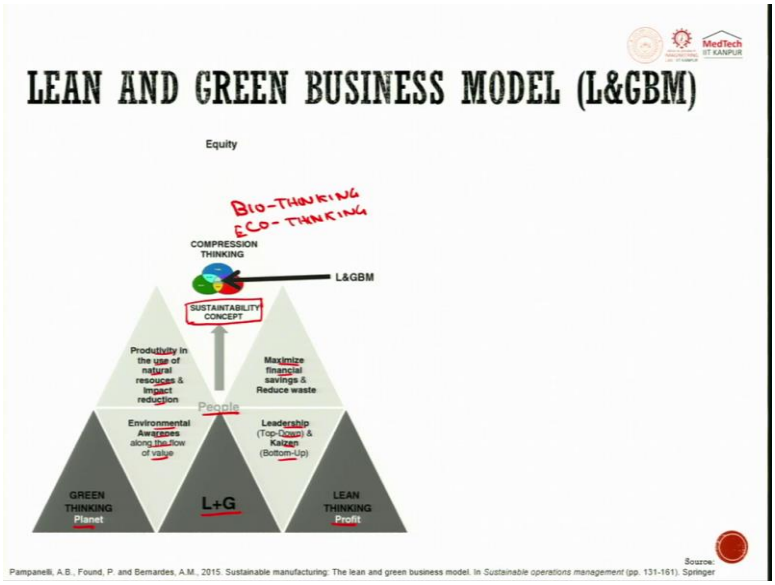

The capability of lean production if we try to say or this model that is given by Pampanelli et al., in 2015 in their research on lean and green business models, they say that sustainability concept or compression thinking, the lean and green business model as it is mentioned in the previous slide has the planet, profit and people as part of it.

So, these 3-pyramid got ‘triple bottom line’ could also be put as, so, this economy is profit. If we put triple P, then societies, people then environment is planet. See again, they say the lean and green work together with the people. So, people have to work together with them taking into account environmental awareness along with the flow value.

The leadership that is from top to down and Kaizen approaches that is from bottom to up, taking the customer ideas and taking them to above that is bottom to up that is a Kaizen approach. Then, productivity in use of natural resources, impact reduction, maximize financial savings, to have the overall sustainability concept, which tells that the thinking has to be from bio viewpoint or economy or the green viewpoint.

So, bio thinking or eco thinking if I say, it is ecology thinking has to be instituted in your businesses. So, it has their certain stages in the improvement, the basic discipline or the safety or the morale is kept into account. Then the quality has to be good, and the costs have to be reduced, and delivery of the goods has to be in proper way, flexibility could also be there, cost reduction could also be taken. These are all general things, that we take care in the lean viewpoint.

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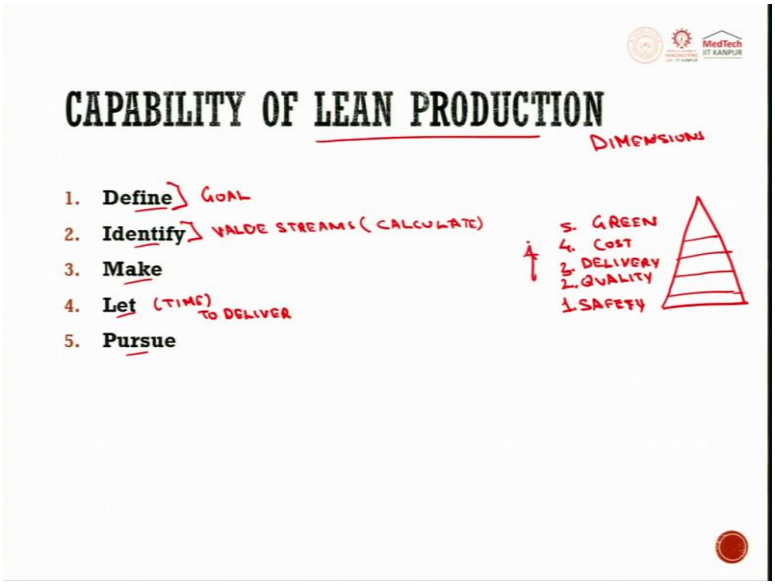

From the green viewpoint, generally, there are certain principles that we try to put here, In the green if we say in the green production, define, identify, make, let pursue are the 5 steps. Define means, we try to define the specific value, we try to define precisely, what perspective of the end customer in terms of specific product or specific capital capabilities are required at specific time. So, this is the complete definitions that is trying to confine our goal.

So, what is our goal? Then, we try to identify the value streams, what value streams are there that is we try to calculate. Then, we try to make the value flow, then, we let the customer pull the value that a design provides what customer wants and only when the customer wants, is the time, is also one of the sectors that is taken into account when you try to let it go.

Then, we try to pursue the perfection that is we strive for perfection by continuously removing the successive layers of waste and try to uncover them. So, this is how it goes, along with this. There are certain dimensions that are always taken into account for example, safety as 1 dimension, I will put dimensions here, number 2 we have quality, I will better put them in the bottom to up approach.

Dimensions are number 1 safety, then we have quality of the product, delivery that is when does the customer required because the cost or the transportation, the fuel used, the carbon footprint also is there in the delivery of the product. So, when this delivery required, I said, the Let is time to deliver actually, so delivery.

Then, next factor comes the cost and the last factor becomes as the greenness. So, this is if I put it up why have I put it from bottom to up. So, because it is something like this first, we considering the safety of the product, the products are designed, then the jot down, quality, then delivery, cost reduction, then only we have green or this is how it goes in lean.

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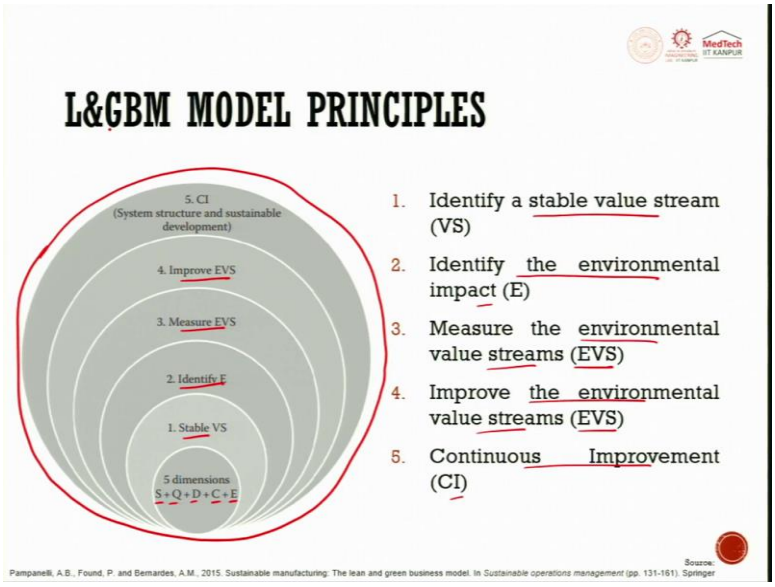

So, identify the stable value stream, identify the environmental impact, measure the environmental value streams, improve the environmental value streams, continuous improvement. This is what lean and green model is suggested by the researchers, they say value stream when you talk about when they can call it green stream or green value stream.

There is something known as value engineering as well, value engineering job plan one of the previous courses I have also designed a Value Engineering Green Plan. Value engineering majorly focus on the function of the product not the product as the overall system. What is the function or what are the primary and the secondary functions, the product is trying to fulfill in that the job plan?

How do we employ the value engineering, green plant has the evaluation factors as the green factors as well? So similarly, the model provided by these researchers they say identify the fundamental impact as well when you are trying to put the value streams. So, they call it EVS, environmental value streams. So, they improve the environment value streams then, improve it continuously that is how it goes.

They say all the dimension's safety, quality, delivery costs environment; all the dimensions are taken into account, these are all the 5 dimensions. So, we try to develop a stable value chain system, we identify the environmental impact, we measure the environmental value stream, try to improve the environmental value stream then continuously keep on doing to have the overall L&GBM, that is lean and green business model.

So, this is one of the models selective, there are multiple models developed by many researchers, you can see 10s of models available or published by different researchers when they try to talk about sustainable manufacturing. I have picked this one, because this is closer to metal additive manufacturing when you are trying to see.

So, how do we keep the system lean when I say lean also topology optimization that we have studied in the previous lectures plays an important part into it. With this I will have to have a break in this lecture. I will meet in the second part of the lecture on sustainability in metal additive manufacturing. We will see the life cycle impact analysis; we will see the circular economy as certain other models. Thank you.