Introduction to Sustainable Manufacturing

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Abstract Sustainability refers to the use of available resources in such a way that their scarcity does not affect the future generation. Nowadays, another word that goes hand in hand with sustainability is "Green". Though *sustainability* and *green* have different definitions, they are used synonymously in the context of the present scenario in manufacturing. In the manufacturing industry, the application of less polluting energy sources, recycling of raw materials, and using processes that are less harmful to the environment are some of the methods that can contribute toward achieving sustainability. Sustainable manufacturing is a concept that has been evolving continuously since its inception. To realize sustainability in manufacturing, the idea of sustainability must be accompanied by certain tools and methods along with implantation policies. One such method to maintain sustainability is to reduce the amount of carbon emission during manufacturing. This chapter discusses

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different aspects of sustainability in the context of manufacturing. The strategies to attain the goal of achieving sustainability in manufacturing have been explained elaborately. Moreover, different approaches adopted to maintain sustainability in the field of manufacturing have been reviewed and extensively discussed.

Keywords Sustainable manufacturing · Outcome · Impact · LCA · Methods · Tools

1 Background and Rationale

These days, humans are consuming the natural resources available on the earth at such a rapid pace that it has become an alarming situation for whole mankind as it takes centuries for these resource materials to get generated. From years 1950–2005, the worldwide consumption of natural gas and oil increased by 14 times and 6 times, respectively. If this trend of increasing consumption of natural resources continues like this, then our future generation will have to face the unavoidable circumstances of the scarcity of resources. Moreover, the lifestyles of the developing society around the globe upgraded by the advanced technologies play a vital role in maintaining the limit of resource consumption. These all concerns lead to the necessity of sustainability which means utilization of the resources in such a way that it does not compromise the fate of our future generation. We, humans, must be concerned about maintaining the balance of nature keeping the fact in mind that nature may be both rigid and fragile at times. The more we exploit nature the more we are closing toward the threshold point where the ecological balance will be shattered and it will affect every specie on the planet.

The definition of sustainability was first proposed in the year of 1987 (Brundtland report) which mentioned that unwanted changes were occurring in our surroundings including the atmosphere, animal habitat, forest, water, and soil [1]. In the context of manufacturing industry, a sustainable approach of manufacturing a product encompasses the minimization of wastes that are produced during the entire life cycle of the product and the reduction of its adverse effects on the environment.

2 Why Sustainable Manufacturing?

Sustainable manufacturing has emerged as one of the most important areas of research during the last few decades. It is a concept that encompasses the design of manufacturing processes and products along with their planning and control which lead to the identification, quantification, assessment, and management of the manufacturing waste flow to the environment with the ultimate aim to reduce the impact on the environment while also giving efforts in maximizing the efficiency of the available resource on the planet earth.

Fig. 1 Possible outcome of sustainable manufacturing

The development of a country vastly depends on its manufacturing sector which creates numerous opportunities of employment, enhances the standard of living, and adds to the growth of the country economically. Therefore, manufacturing is regarded as the driving factor for the prosperity and welfare of a society. But, at the same time due to its dependency on natural resource consumption and uncontrolled generation of wastes and gaseous emissions, manufacturing creates concerns for the very existence of our environmental balance. The direct and indirect contribution of manufacturing to the depletion of the resources available in the nature leads to deteriorating the effect on the health of human and other living beings and most importantly it affects the ecosystem. Therefore, there is an urgent need to understand and implement the concept of sustainability in the manufacturing sector. The motive of sustainable manufacturing is to make products using the minimum amount of energy and available resources. Sustainability must be exercised not only during the production stage but throughout the whole life cycle of the product.

Today, from the pen to the airplane, everything needs to be manufactured. In fact, it is impossible to imagine a world without manufacturing industry. For every manufactured product, we need resources and energy and with each gram of resource consumption, there comes the concern over the limited natural resource that is available on earth. Therefore, it is very important to realize sustainability in the context of manufacturing throughout the whole life cycle of the product. Sustainability can enhance the efficiency of the manufacturing processes by cutting down the cost that is involved in resource and energy consumption and also by reducing the wastes involved in a manufacturing process. A manufacturing industry can also avail the benefit of less costs involved in different environmental regulatory if it adopts sustainability at the very beginning of its setup. Other benefits of adopting sustainability

in a manufacturing industry include better hiring of employees and their enhanced retention rate. In sustainable manufacturing, the emphasis is also on minimizing the number of parts that consumes resources. In other words, we need to optimize the use of materials to get the required product which demands more efficient use of the available resources. To reduce the harm that a manufacturing process can bring upon the environment, sustainable and green manufacturing is the need of the hour. Figure 1 presents the possible results of adopting sustainable manufacturing.

3 Impact of Manufacturing Processes on Environment

The most concerning effects of manufacturing processes on the environment are consumption of natural resources at a rapid pace that may lead to an imbalance in nature and also disturb the demand and supply chain, rise in the emission of greenhouse gases leading to unwanted changes in the climate worldwide, and increase in the industrial waste resulting in environmental pollution. There are many tools for assessing the environmental impact of a manufacturing process or a product, carbon footprint analysis, the impact equation, and life cycle assessment being a few of them. Manufacturers around the globe have started understanding the importance of sustainable manufacturing and hence, efforts are being made to counter the issues related to environmental impact of the manufacturing industry. But the harsh truth is that even if manufacturers succeed in reducing the amount of substances that are potential to pollute the environment, it will be a long way to arrive at sustainability.

3.1 Carbon Footprint Analysis

The factor that contribute mostly to global warming and climate change is the level of emission of carbon and its compound [2]. The rise of the automobile section of the manufacturing industry has immensely contributed to the emission of greenhouse gases (GHGs) and this is true for the entire world [3]. Carbon foot prints (CF) represents the amount of carbon emission that are potentially polluting the atmosphere during every operation that is performed on a product starting from raw material to its disposal. Carbon footprint analysis (CPA) involves the process of determining the quantity of GHGs produced during the life cycle of a manufactured product and it is presented as equivalent carbon dioxide (eCO2) [4]. The protocol that is to be followed regarding emission of GHGs was developed by World Resources Institute and World Business Council for Sustainable Development and it is considered as the prevalently used standard for the measurement of emission of carbon worldwide [5]. In recent times, the concept of CPA has become popular worldwide among the general section of people in context of their responsibilities in prohibiting global warming [6].

So, we now understand that CPA is an analytical method to quantify the effect of carbon emissions including GHGs produced by various industries or organization. For any organization, the emission of GHGs can be categorized as—(a) direct emission, (b) indirect emission, and (c) emission due to electricity [7].

On a global basis, the production sector is responsible for 20% of overall carbon emissions which consumes 54% of the total energy worldwide from various sources. Product carbon footprint (PCF) is a concept where the total emission of GHGs is measured for a particular product and it is considered as the very initial step towards minimizing CF in a manufacturing industry [8]. Some of the most emitted GHGs are briefly explained here:

(a) Carbon dioxide (CO_2): CO_2 emissions generally result due to burning of solid waste, fossil fuels, and products made of wood and tree. It can be also observed in the chemical reactions involved in manufacturing of cement.
(b) Methane (CH_4): This gas is released while producing and transporting natural gas and coal. It can also be emitted from landfill decay, livestock, and agricultural activities.
(c) Nitrous oxide (N_2O): this type of emission is the result of emissions result of industrial and agricultural activities. Combustion of solid waste and fossil fuels is also a reason for such emission.

3.2 The Impact Equation

There is another technique to assess the impact of technology on the environment which is known as the impact equation [9]. The main components of the impact equation are (i) population (P), (ii) affluence (A) measured by gross domestic product per person, and (iii) technology (T) measured as impact per unit of gross domestic product. As much cannot be done about population growth and also people cannot be discouraged from aspiring for more affluence, the only factor responsible for reducing the impact is technology.

3.3 Life Cycle Assessment

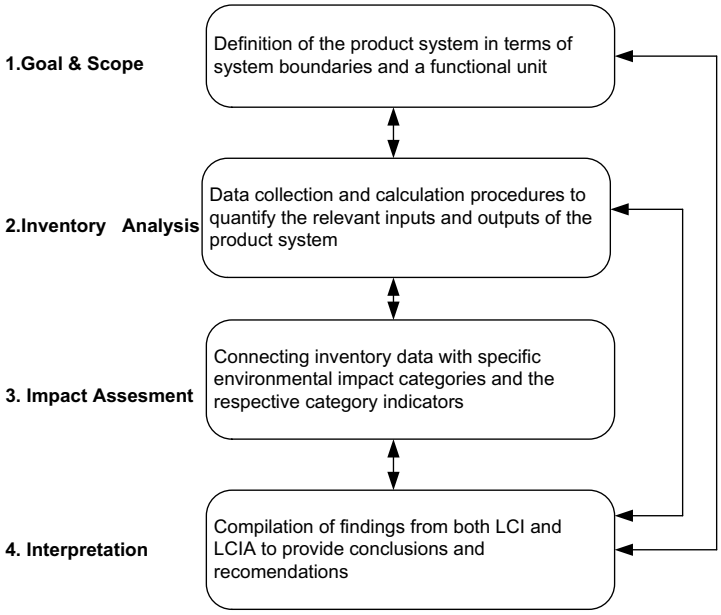
In order to implement the concept of sustainability in manufacturing emphasis should be given to the life cycle assessment (LCA) of the product. LCA is a method applied to analyze and quantify the impact of a process, product, or activity on the environment. In the beginning of civilization, human used to believe that there was an inexhaustible amount of resources on the earth and they had little idea of what consequence their daily activities can bring upon the environment. Later, people started to realize the limitation of the quantity of available resources that can be used to meet their needs. Also, the pollution created by the wastes produced in industries started being noticed by people and they started understanding its menacing effect on the environment.

With time, different tools to study and assess the impact of a product or a process on the environment got developed by scientists and researchers, LCA being one among them. LCA is used to study the overall impact of any process or product on the environment which is the sum of the different stages throughout the whole life cycle. According to ISO 14040-14,044, the goal of LCA is to compare the environmental performance of products in order to be able to choose the least burdensome. The term "life-cycle" refers to the notion that for a fair, holistic assessment the raw material production, manufacture, distribution, use, and disposal (including all intervening transportation steps) need to be assessed. The concept can also be used to optimize the environmental performance of a single product (Ecodesign) or that of a company as per ISO 2006 [10].

LCA, in fact, is one kind of analysis tool used for the evaluation of the potential effect of a material or a product on the environment or the ecological system to be precise, right from the production stage to its end of life. It is a tool which is accepted internationally from the perspective of environment as it is a holistic approach having standardized and scientific methodology. LCA facilitates an assessment of goods, products, and services which is systematic and quantitative, in terms of impact on environment, human health, and consumption of resources. In Fig. 2, the four steps of LCA study according to ISO 14040 are shown. All the inputs and outputs of the boundaries of the system are needed to be quantified and they should be assigned to the various processes and stages of the products. The typical inputs are raw materials and energy and typical outputs are emissions (air, water, and soil) and wastes. The basic steps to be followed while performing LCA (according to ISO: 14,044:2006) are presented in Fig. 2.

4 Methods and Tools to Maintain and Assess Sustainability in Manufacturing

Although, by now, the importance of sustainability in manufacturing has been understood all over the globe, there must be some well-designed systematic approaches or methods that can help a manufacturing industry or organization to fathom the environmental impact of any manufactured product or the processes involved in manufacturing it and provide a solution to improve its environmental performance. These methods and tools help the organization to understand the way the product interacts with the environment. These tools are generally termed environment management tools. The determination of the effectiveness and wastage resulted from a product by considering the inputs given to manufacture it along with the plausible output is also important. Moreover, the cost consideration is also an aspect to be considered while using these tools. The total cost related to a product consists of the costs related to acquiring raw materials, labor cost, cost of using energy, and cost of waste disposal. Product life cycle of also an important aspect with respect to its environmental impact. It is important for the manufacturers, as well as the users, to understand that short



LCI: Life cycle inventory
LCIA: Life cycle inventory analysis

Fig. 2 Steps for LCA study according to ISO: 14,044:2006

life cycle of a product leads to a reduced adverse impact on the environment. The processes required to get the desired product can be divided into three phases. The first phase is the conceptualization of the required product and then designing it in detail. Then, comes the production or manufacturing phase. The last phase is the operational use and system support.

In the manufacturing sector, there is a concept of three "R"s to maintain sustainability and those are **R**educe, **R**euse, and **R**ecycle.

Reduce:

(a) We must reduce using non-degradable disposable products.
(b) We should also try eliminating the excess use of materials for packaging.
(c) Using soft copy (email) instead of hard copy (paper) when exchanging information or data is another important thing to be considered.
(d) We should opt for buying products that are durable and repairable.
(e) Increase the efficiency of the raw materials while using them.

Reuse:

(a) We should think about how we can reuse waste/scrap materials.
(b) Try to repair the old instrument or machine rather than buy a new one.

Recycle:

(a) We should accustom us to use recycled materials such as plastics, metals, and papers.
(b) Use of hazardous materials or products should be avoided.

Studies on sustainability reveal that there is a diversity of various approaches for developing sustainability assessment tools. In the study carried out by Feng and Joung, [11], an analysis of 13 mostly discussed indicators that are used for the assessment of sustainability was performed. It was concluded from the study that most of those indicators focused on only the externally developed reports and not on the internal information that can be used by the decision-makers. In another study [12], researchers carried out an analysis of eight different tools for the assessment of sustainability and found that some of those tools focused more on the assessment of the product rather than the adopted manufacturing processes. A few of the other tools helped in assessing the environmental characteristic of the product. Some other factors that are used to measure sustainability are index for sustainable development of composite [13], indices for sustainable production [14], index for sustainable manufacturing [15], etc.

Marconi and Menghi [16], in their article, proposed a tool and method for sustainable manufacturing. The application of the tool was discussed in the context of manufacturing industry that dealt with components of automobiles. The proposed too worked on the process of mapping of the activities involved in manufacturing a product with the used resource materials. The method was based on Resource Value Mapping (RVM) as explained by Papetti et al. [17]. The first step of the RVM method is defining the goal consisting of all the data and information required for the subsequent steps. In the second step which is basically mapping of the processes, it is required to analyze the production system in order to finalize the layout for plant or production line. All the important data are collected in the third step. The fourth step involves assessing the key performance indicators of the system and their representation in simple and easy-to-interpret ways. The last step is about identification of the scope of improving the ways of mitigating the complexities recognized in the previous step and also, verification of the potential efficiency, environmental and economic benefits.

5 Degree of Sustainability

The *degree of sustainability* may be defined as the extent to which a process or product is made green or sustainable. For example, if a person is using a product that is solely made from a bio-based and biodegradable polymer, it can be considered that the product has the highest degree of sustainability or degree of greenness. The reason is that using a bio-based and fully biodegradable polymeric product results in two positive outcomes. First, it totally avoids using synthetic polymer which is made

from fossil fuel and minimizes the consumption of the available resources. Secondly, being fully biodegradable, it eliminates the adverse impact on the environment totally.

There are certain products that are partly sustainable. Let us take an example of a product which is made of a composite material containing biodegradable polymer as the matrix phase and a ceramic powder as the reinforcement or the filler materials. Now, after the useful life of the product, when it is disposed of for biodegradation, it cannot degrade fully due to the presence of non-biodegradable ceramic content. Therefore, it can be said that this product was partly green or sustainable or the degree of sustainability is less than that of the previous example. There is another category of products or materials which are totally non-biodegradable, for example, single-use plastic bags or plastic water bottles. These materials can never degrade naturally and therefore another approach such as incineration is taken to degrade them which may eventually create more hazards for the environment. These types of products are said to have zero degrees of sustainability.

6 Conclusion

This chapter describes the role of sustainability in manufacturing sector. Different ways to assess the impact of manufactured products or processes were explained extensively. The most important factors for assessing the impact of manufacturing on the environment are carbon footprint analysis and life cycle assessment. There are different methods of maintaining sustainability in an organization, particularly in a manufacturing industry. Also, different tools are adopted to assess the sustainability or greenness of a product or process. The concept of reduce, reuse, and recycle is the need of the hour for every manufacturing around the globe in order to achieve sustainability. With the understanding of the approach of sustainability, one must be aware of the degree of sustainability that a product exhibits. Finally, it can be said that survival of mankind and all the creatures on earth depends greatly on the fact that it's time we chose a greener and sustainable lifestyle.

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