sustainability

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Review

Design for Sustainable Manufacturing: Approach, Implementation, and Assessment

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Abstract: The implementation of sustainable systems is an essential requirement in modern manufacturing, in order to minimize the environmental and health concerns, and conserves energy and natural resources. The sustainable manufacturing approach is identified through three main levels, namely: product, process, and system scales. The interactions among these levels provide the required sustainable target. To achieve a sustainable manufacturing system, it is very important to understand and define the concepts and needs related to the sustainability approach. In addition, defining and understanding the implementation steps as well as the assessment method to build a sustainable manufacturing system is required. In this work, a study discussing the sustainable manufacturing approach is presented in terms of concepts, implementation steps, and assessment methods.

Keywords: sustainability; manufacturing; assessment; implementation

1. Introduction

It is a well-acknowledged fact that the major environmental concerns have arisen because of the pollution and consumption of natural resources. Thus, the implementation of sustainable systems is an essential requirement in modern manufacturing to address these concerns and to present effective solutions. There is no universal definition for the term sustainability; however, the most acceptable illustration of this term was proposed by Norway's previous Prime Minister and Director-General of the World Health Organization (WHO), Gro Harlem Bruntland, who expressed it as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Jawahir and Wanigarathne showed that the main aspects of sustainability are focused on the environmental, economic, and social directions, in order to achieve better requirements through effectively utilizing available resources [1–3].

Each sustainable aspect has specific objectives that should be achieved in order to create and implement the efficient term of sustainability. The main objectives of social sustainability are focused on health improvement, safety, quality of life enhancement, and ethics. When looking at the environmental sustainability, clean air, water, soil, regulations implementation, and eco-balance efficiency support this goal. With respect to economic sustainability, the main pillars are product and process development, new employment, and large-scale new business opportunities [1,4].

The concept of sustainable manufacturing is identified and analyzed through three main levels, namely: product, process, and system levels, as shown in Figure 1. The interaction among these levels provides the required sustainable target. With regard to the product level, the perspective of sustainable manufacturing focuses on the new 6R approach (i.e., re-duce, re-design, re-use, re-cover, re-manufacture, and re-cycle) instead of the 3R approach (i.e., reduce, reuse, and recycle), as it theoretically achieves a closed loop and multiple life-cycle paradigms [5–7]. At the process level, reducing energy consumption, hazards, and toxic waste is accomplished through using an optimized technological process associated with an effective process planning methodology, while using an efficient supply chain system considering all life-cycle stages (i.e., pre-manufacturing, manufacturing, use, and post-use) provides an effective sustainable system [3,8,9]. The expectations of a sustainable manufacturing process are concluded as follows [1,2,4]:

- Energy consumption reduction.
- Waste elimination/reduction.
- Product durability improvement.
- Health hazards and toxic dispersion elimination.
- Higher quality of manufacturing.
- Recycling, reuse, and remanufacturing enhancement.
- Development of renewable energy resources.

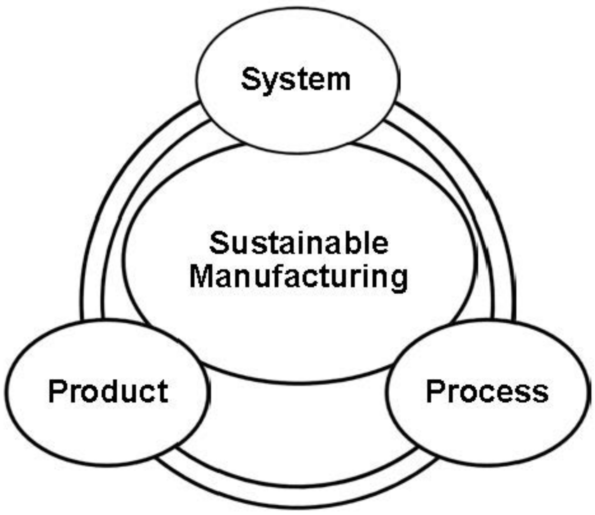

Figure 1. Sustainable manufacturing levels.

Therefore, in this work, a review study that discusses the sustainable manufacturing approach is presented in terms of concepts, implementation techniques, and assessment methods.

2. Sustainable Manufacturing Elements

The evolution of sustainable manufacturing is shown in Figure 2. It can be seen that sustainable manufacturing evolves through several generations, namely: traditional manufacturing; lean manufacturing; green manufacturing; and, in its most developed phase, sustainable manufacturing [10,11].

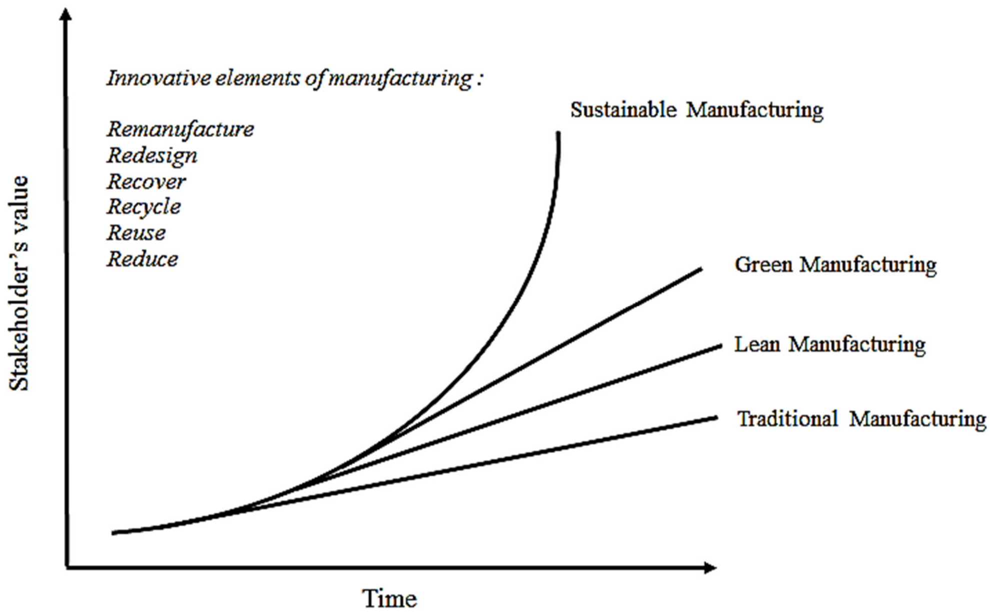

Figure 2. Sustainable manufacturing evolutions [10].

The 6R approach adds three new elements to modify the classic approach (3R); these elements are recover, redesign, and remanufacture. The recover stage deals with collecting end-of-life products through post-use activities. On the other hand, the redesign element provides sufficient environmental consideration by simplifying the future post-use processes, while the product performance can be improved through the remanufacture element, as it works on saving natural resources, energy, cost, and on reducing the generated waste [1,2]. One of the most important aspects of building and enhancing sustainable manufacturing systems is obtaining some basic keys for implementation. It can be seen from the open literature [4,12–14] that implementation of the sustainable model is addressed by three major phases, as follows:

- **Research**: to develop, evaluate, and examine the specific sustainability requirements, such as energy and resource use, pollution, and climate change impacts. This phase of the model has a high potential as it helps to ensure sustainability at the pre-competitive level and focuses on the manufacturing environmental issues;
- **Development**: to improve the environmental performance, such as environmental footprint assessment, life cycle analysis, and design for environment, by using appropriate methods and tools [15,16];
- **Commercialization**: to refine the previous phases and co-operate with suppliers, vendors, and customers.

3. Sustainable Manufacturing: Needs and Concepts

To achieve a sustainable manufacturing system, it is very important to understand and define the needs related to the sustainability approach. It can be seen from the open literature [12,17,18] that building a sustainable manufacturing system can be accomplished by employing three basic keys, which are used to describe and define the sustainable manufacturing needs, namely:

- **Information**: to make an effective assessment by providing the required quantitative and qualitative information;
- **Management and culture**: to encourage and develop a sustainability-oriented culture in the organization through specialized sustainable departments inside the companies;
- **Procedures**: to ensure applying the objectives and strategies for sustainable organization effectively.

Additionally, a number of needs are required to improve the manufacturing sustainability performance. These needs are summarized as follows [12,19–21]:

- **Concepts**: present comprehensive analysis of the economic, social, and environmental clusters, as well as other relevant considerations;
- **Methods and tools**: development, improvement, and enhancement of smart tools and methods to support the concept of sustainability;
- **Data**: to support the environmental impact and sustainability assessments, more detailed, comprehensive and robust data are needed across the overall product life cycle;
- **Manufacturing practices**: to build sustainable indicators for measuring and monitoring purposes to increase the sustainability awareness among suppliers and customers;
- **Government policies**: to achieve incorporation between companies and government through sustainable programs, and environmental factors–clean processes policy;
- **Research**: academic and industrial research is needed to enhance the sustainability system by focusing on the manufacturing, design, and environmental aspects;
- **Integration**: for all previous needs to achieve an integrated system, which represents the environmental, economic, and societal sustainable aspects.

4. Design for Sustainable Manufacturing

In terms of design for sustainable manufacturing, several objectives should be considered to achieve the desired target for process, product, and system scales. These objectives are provided as follows [1,22,23]:

- Design for repair, reuse, and recycle.
- Design for waste and hazards minimization.
- Design for product disassembly.
- Design for continuous improvements.
- Design for energy efficiency.
- Design for remanufacturing.
- Design for optimal materials use.
- Design for cost effectiveness.

Also, the term of "design for sustainable manufacturing" can be expressed as a unique loop, which includes the integration of information and substance loops across life cycle stages, as shown in Figure 3 [22]. The main pillars of design for sustainable manufacturing, based on product and process levels are design for optimum environmental impact, design for resource utilization and economy, design for manufacturability, design for functionality, design for social impact, and design for recyclability and re-manufacturability. In terms of design for environmental impact [15,24], the main responsibility is dealing with environmental effects, co-balance, and efficiency. Regarding design for resource utilization and economy, it mainly concerns power consumption, energy efficiency, material utilization, operational cost, and using renewable energy resources [2,3,25]. Additionally, the design for manufacturability [26] is related to improving the manufacturing methods, packaging, assembly, and transportation and storage techniques. Another pillar is design for functionality, which includes different aspects, such as durability, ease of use, serviceability, upgradability, ergonomics, function effectiveness, and reliability [2,27,28]. Operation safety, health-wellness effect, and ethical responsibility are the main objectives related to the design for social impact [29–31]. The last pillar is design for recyclability [32] and re-manufacturability [33,34], which is mainly focused on offering advanced and smart techniques for re-manufacturing and recycling operations to increase the efficiency of materials and energy use.

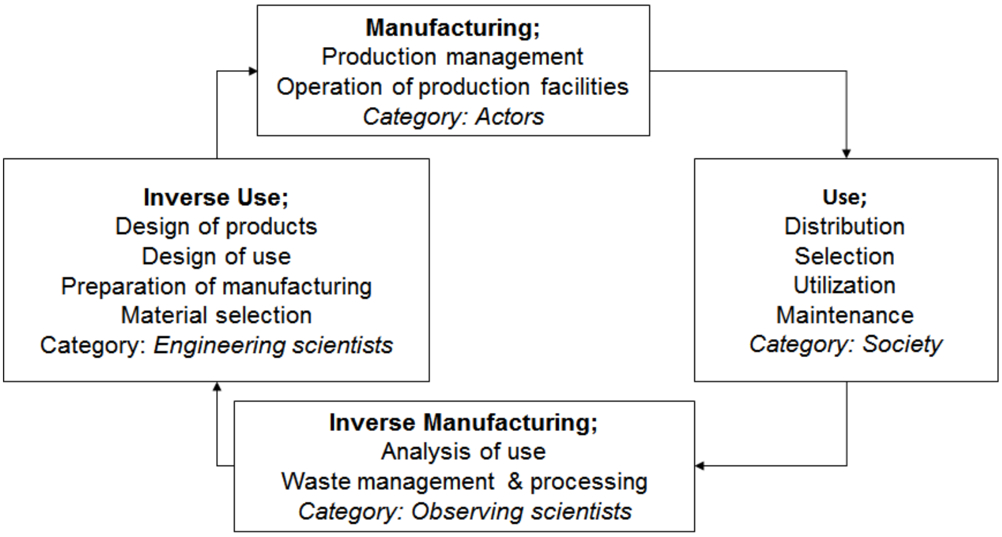

Figure 3. Design for sustainable manufacturing: cycle and elements [22].

5. Practice and Implementation of Sustainable Manufacturing

Once the models, elements, and needs of sustainable manufacturing are defined, it is necessary to understand and obtain the required methodologies to implement an effective sustainable manufacturing system. In this section, the practice and recommendations for the implementation of sustainable manufacturing concepts are discussed. To achieve a sustainable manufacturing system, defining and implementing some practical aspects through the product, process, and system levels are required. Some of these aspects are summarized and presented as follows [35–38]:

- Applying principles of utilized materials and inputs, which are non-hazardous and recyclable;
- Developing and planning of production processes to reduce the consumption of energy, materials, and water;
- Using renewable energy that does not affect the natural environment;
- Developing product design to be reusable, re-manufacturable, or recyclable;
- Expanding the design concepts of using fewer resources and applying easy-to-repair techniques;
- Using efficient transportation and logistics systems.

The implementation steps to achieve the sustainable manufacturing approach are varied based on the implementation difficulty level. These steps are provided, as shown in Figure 4.

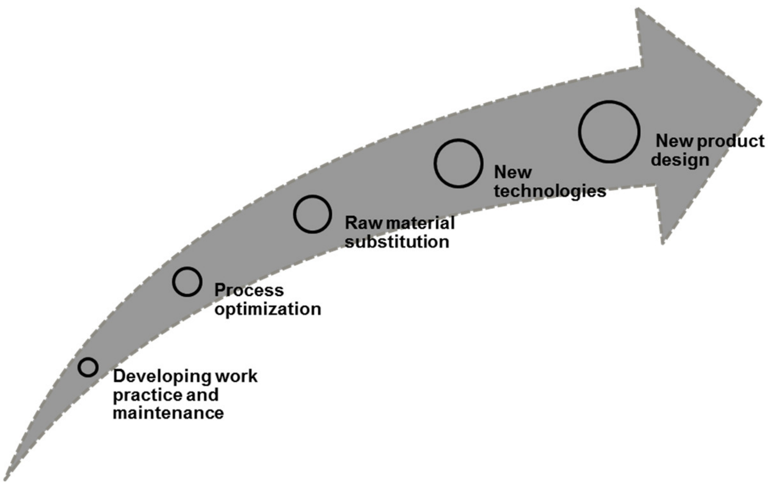

Figure 4. The implementation steps of the sustainable manufacturing approach.

The description of each implementation step is discussed in previous studies. The summary of these steps along with their descriptions are summarized as follows [39–42]:

- **Developing work practice and maintenance**: This step is called the housekeeping step, and it is considered as a simple action to accomplish effective monitoring, inventory management, and scheduling in all production operations (e.g., reducing loss from leaks, keep equipment's maintaining properly, sustainable training programs).
- **Process optimization**: In this step, development in manufacturing processes is required to minimize waste, conserve raw materials, and reuse waste materials. Examples of actions during these steps are changing the steps in a specific process, determining the optimal settings for each operation, and or rearranging machines' locations to minimize the total required movements. Also, the implementation of energy-efficient technologies offers significant effects, which support the sustainable manufacturing concepts. For example, using minimum quantity lubrication and dry cutting [43], cryogenic approach [44], waste management principles [45], modeling and optimization approaches [46,47], and artificial intelligence methods [48].
- **Raw material substitution**: The main objective of this step is to replace hazardous materials and chemicals (high environmental impact) with sustainable materials (low health and environmental impact). The output of the current step contributes to reducing environmental and health concerns, as well as avoiding the regulatory costs associated with the storage and disposal of materials.
- **New technologies**: This step depends on using more energy-efficient systems that enhance the environmental impact performance, as they have effective capabilities of saving heat and energy. However, for these technologies to have an effective impact to achieve sustainable systems, they need huge capital investment (i.e., initial costs problems).
- **New product design**: This is considered the most difficult implementation step as it needs to transfer the whole system from the ground up to be greener (more sustainable). Some development keys to achieve this step are mentioned in Section 3; for example, smart methods, research, integration, and manufacturing practices.

It should be stated that many attempts have been presented in previous studies to implement the sustainable manufacturing concepts, and to link the sustainability aspects (e.g., energy consumption, environmental and health concerns, and waste management) with real manufacturing needs. Some of these studies are presented in Table 1.

Table 1. The link between the sustainable manufacturing concepts and recent technologies. ADI—austempered ductile iron; 6R approach—re-duce, re-design, re-use, re-cover, re-manufacture, and re-cycle.

Reference	Sustainable Technology	Application
[49]	Using natural biodegradable oils with minimum quantity lubrication (MQL)	Achieve sustainable machining of Inconel 718
[50]	Applying different coolant pressures	Improve the machinability of Inconel 718 and Waspalloy
[51]	Combined using of MQL and cryogenic techniques	Accomplish environmentally efficient machining for difficult-to-cut materials
[52–55]	Application of MQL-nano-fluid technique	Enhancing the machinability of Inconel 718 and Ti-6Al-4V in terms of tool wear, power consumption, and surface quality
[56,57]	Employing MQL with vegetable oil	Achieve sustainable machining of ADI
[58]	Application of 6R approach and waste management techniques	Enhancing the construction waste recycling
[59]	Additive manufacturing and nano-technology	Developing the characteristics of the final printed component
[60]	Implementation of standard health and environmental regulations	Reducing the health and environmental concerns associated with machining operations

6. Assessment of Sustainable Manufacturing Approach

Once the implementation stages are defined, it is also necessary to have a solid assessment model to evaluate the sustainability of the manufacturing systems. It has been obtained from the open literature that five major elements are mainly used to assess the sustainability aspects of the manufacturing systems. These elements are as follows: manufacturing costs, environmental impact, waste management, energy consumption, and personal health and safety, as has been mentioned in some previous studies [61–64]. A summary for each element (i.e., sub-clusters, indicators, and measurements methods) is summarized as shown in Tables 2–6 [4,27,65]. It has been obtained from previous studies [27,66–68] that some of these elements (i.e., energy consumption, manufacturing costs, and waste indicators) can be modeled using analytical and numerical models; however, other elements, such as personal health and safety, as well as environmental impact [69], can be expressed depending on the designer's experience and judgment. A sustainability assessment schema that obtains the integration and analysis of all sustainable elements is provided, as shown in Figure 5. The assessment method can provide the optimal operating conditions (levels). It can be seen that the effective assessment method includes the integrated effect of all of the studied sustainable elements, as presented and discussed in some previous studies [61,70]. After that, a suitable optimization methodology/loop (considering the system constraints) is employed to find the optimal/sustainable operating levels (acceptable sustainability level). The acceptable sustainability level is defined based on the designer's experience and judgment.

Table 2. Sub-clusters, indicators, and measurement methods for manufacturing costs [6,27].

Sub-Cluster	Individual Metric	Measurement Method
Direct cost	Labor cost	Total employee payment to machining positions/total number of product units made
	Operation energy cost	Total cost for energy consumed in machine operation/total number of product units made
	Consumable-related cost	Total cost of consumables/total number of product units made
	Cutting tool-related cost	Total cost for purchasing new tools + cost for regrinding used tools − cost of recycling used tools)/total number of product units made
	Packaging-related cost	Total cost for purchasing new packages + used package treatment fee)/total number of product units made
	Scrap cost	Total cost of scrapped product units/total number of product units made
	Cost of by-product treatment	Total cost for by-product treatment which is not covered above)/total number of product units made
	Training cost	Total training cost/number of employees
Indirect cost	Indirect labor cost	Total indirect labor cost/total number of product units made
	Maintenance cost	Total cost for equipment maintenance/total number of product units made
	Audit and legal cost	Total cost of audits, legal services, and litigation/total number of product units made
	Cost of safety investment	Total cost of equipment/total number of product units made
Capital cost	Cost of depreciation	Total depreciation of storage and fixed facilities/total number of product units made
	Cost of tools/fixtures investment	Total cost of jigs and fixtures/total number of product units made

Table 3. Sub-clusters, indicators, and measurement methods for personal health and safety [6,27].

Sub-Cluster	Individual Metric	Measurement Method
Working environment conditions (health)	Chemical concentration	Chemical concentration in the working environment (break down to the chemical list
	Mist/dust level	Micro-particle concentration in the working environment
	Noise exposure	Noise level in the working environment
	Temperature	Temperature level in the working environment
	Other hazardous exposure	Hazardous exposure level in the working environment
Physical load index	Physical load index	Measured physical load index
Absentee rate	Health-related absenteeism rate	Health-related absenteeism rate
Working environment conditions (safety)	Exposure to corrosive/toxic chemicals	Number of points with corrosive or toxic chemicals/total number of employees (break down to chemical list
	Exposure to high temperature surfaces	Total number of high-temperature points exposed to the operator/total number of employees
	Exposure to high-speed components and splashes	Total number of points with high-speed components exposed to the operator/total number of employees
	Exposure to high-voltage electricity	Total number of points with high-voltage electricity exposed to the operator/total number of employees
	Other threatening exposure	Total other exposed points with hazardous effects (splash, sparks, high-energy laser, etc.)/total number of employees
Injuries	Injury rate	Total injuries/total number of product units made

Table 4. Sub-clusters, indicators, and measurement methods for waste management [6,27].

Sub-Cluster	Individual Metric	Measurement Method
Consumables	Ratio of consumables recovered	Mass of recovered consumables/total mass of used consumables
	Ratio of consumables reused	Mass of reused consumables/total mass of used consumables
	Ratio of consumables recycled	Mass of recycled consumables/total mass of used consumables
	Mass of disposed used consumables	Mass of used consumables going to landfill/total number of product units made
Packaging	Ratio of used packaging recovered	Mass of recovered packaging/total mass of used packaging material
	Ratio of used packaging reused	Mass of reused packaging/total mass of used packaging material
	Ratio of used packaging recycled	Mass of recycled packaging/total mass of used packaging material
	Mass of disposed used packaging	Mass of used packaging going to the landfill/total number of product units made
Used raw material (chips)	Ratio of used raw material recovered	Mass of used raw material recovered/total mass of used raw material
	Ratio of used raw material reused	Mass of used raw material reused/total mass of used raw material
	Ratio of used raw material recycled	Mass of used raw material recycled/total mass of used raw material
	Mass of disposed used raw material	Mass of used raw material going to landfill/total number of product units made
Scrap parts	Ratio of scrap parts recovered	Mass of scrap part recovered/total mass of scrap parts
	Ratio of scrap parts remanufactured	Mass of remanufactured scrap part/total mass of scrap parts
	Ratio of scrap parts recycled	Mass of recycled scrap part/total mass of scrap parts
	Mass of disposed scrap parts	Mass of scrap part going to the landfill/total number of products made

Table 5. Sub-clusters, indicators, and measurement methods for energy consumption [6,27].

Sub-Cluster	Individual Metric	Measurement Method
Production	In-line electricity consumption	Total electricity consumption of all units and equipment in the line/total number of product units made
	In-line fossil fuel consumption	Total fossil fuel consumption of all units and equipment in the line/total number of product units made
Transportation	Transportation electricity consumption	Total energy consumption of all transportation equipment in the beginning or end of the line/total number of product units made
	Transportation fossil fuel consumption	Total fossil fuel consumption of all transportation equipment in the beginning or end of the line/total number of product units made
Facilities	Electricity consumption on maintaining facility environment	Total energy consumption of all environmental maintenance units and equipment/total number of product units made
	Fossil fuel consumption on maintaining facility environment	Total energy consumption of all environmental maintenance units and equipment/total number of product units made
Production supply system	Electricity consumption of concentrated supply system	Total energy consumption of all supply system equipment/total number of product units made
	Fossil fuel consumption of concentrated supply system	Total fossil fuel consumption of all supply system equipment/total number of product units made
Maintenance	Electricity consumption on maintenance	Total electricity consumption for maintenance operations/total number of product units made
	Fossil fuel consumption on maintenance	Total fossil fuel consumption for maintenance operations/total number of product units made
Efficiency	Energy efficiency	Useful equivalent energy output from the process/total energy input
Renewable energy	Percentage of renewable energy used	Total consumption of renewable energy/total energy consumption

Table 6. Sub-clusters, indicators, and measurement methods for environmental impact [6,27].

Sub-Cluster	Individual Metric	Measurement Method
Energy	GHG emission from energy consumption of the line	Total energy consumption/total number of product units made
	Percentage of renewable energy used	Total renewable energy used/total energy consumption
Water	Total water consumption of the line	Total water consumption/total number of product units made
Restricted material	Mass of restricted materials in disposed consumables	Mass of restricted materials in disposed consumables/total number of product units made
	Mass of restricted material in disposed packaging	Mass of restricted material in used packaging/total number of product units made
	Mass of restricted material in disposed raw materials	Mass of restricted materials in raw material going to landfill/total number of product units made
	Mass of restricted material in scrap parts going to landfill	Mass of restricted material in scrap parts going to landfill/total number of product units made

Table 6. *Cont.*

Sub-Cluster	Individual Metric	Measurement Method
Disposed waste	Mass of non-collected solid wastes	Total mass of non-collected solid wastes/total number of product units made
	Mass of non-collected liquid wastes	Total mass of non-collected liquid wastes/total number of product units made
	Mass of non-collected gaseous wastes	Total mass of non-collected gaseous wastes/total number of product units made
	Mass of solid wastes going to landfill	Total mass of solid wastes going to landfill/total number of product units made
	Mass of liquid waste disposed	Total mass of liquid wastes going to landfill/total number of product units made
Noise pollution	Noise level outside the plant	Noise level measured outside the plant
Heat	Heat generation	Heat generated by the manufacturing line/total number of product units made

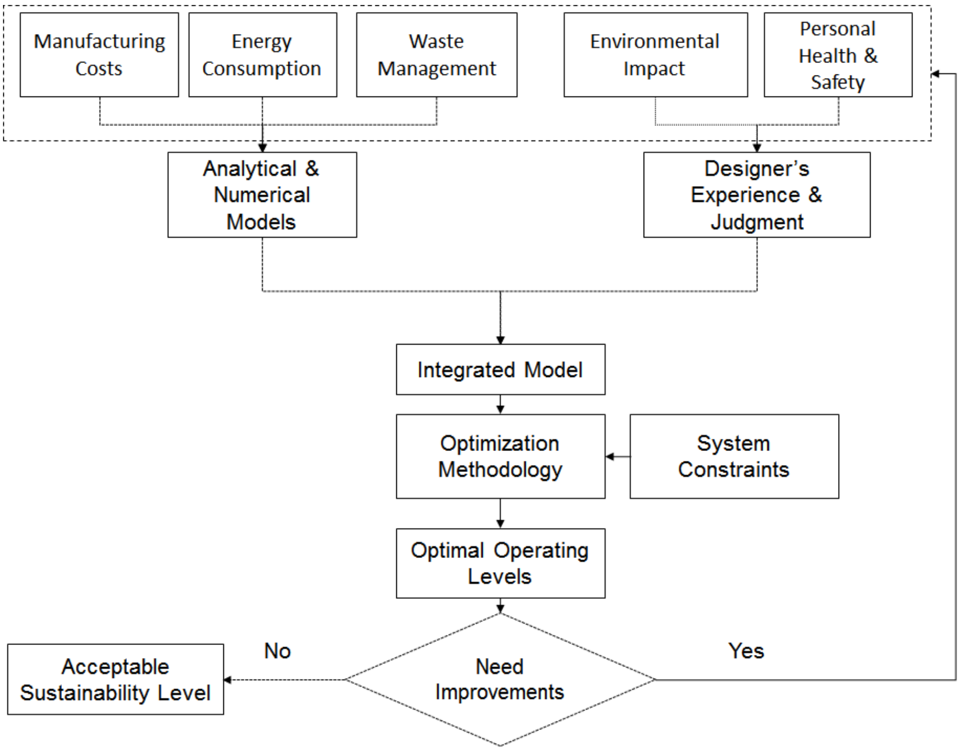

Figure 5. Assessment, modeling, and optimization of sustainable manufacturing systems [61,70].

Additionally, an assessment of sustainable manufacturing from the product perspective can be expressed by three main clusters, which are economic, environmental, and societal aspects, as mentioned in some previous studies [71,72]. Regarding the economical cluster, it includes initial investment, direct and indirect costs, and economic growth benefits and financial losses. The environmental cluster, it focuses on the efficiency of the material and energy use, the end-of-life of the product, and the waste and emissions. In terms of the societal cluster, it assesses the health and safety impacts, employment benefits and characteristics, human rights implementation, and the societal impact regulations. Regarding the system and process levels, sustainability is described through the five pillars (i.e., manufacturing costs, personal health, waste management, energy consumption, and environmental impact), presented in Figure 5. In terms of the product level, another assessment method, which includes the economic, societal, and environmental consideration, can be used. Also, it should be stated that this work is mainly focused so as to achieve a sustainable manufacturing target through obtaining an interaction among the three sustainable manufacturing levels (i.e., system, process, and product). The desired interaction represents an important role for achieving the required expectations of the sustainable manufacturing.

Applying sustainable manufacturing concepts offers various advantages; for example, it can reduce the energy consumption, decrease/eliminate the waste, improve the product durability, achieve better health and safety conditions, and enhance the system and processes overall performance.

7. Discussions and Future Trends

Understanding the needs, implementation techniques, and assessment methods is crucial in order to accomplish an effective sustainable environment. Thus, this work discusses the sustainable manufacturing approach in terms of concepts, implementation, and assessment methods. Also, it should be stated that three main phases (i.e., research, development, and commercialization) are used to address the sustainable manufacturing approach in order to achieve the main sustainable manufacturing expectations (i.e., reduce the energy consumption, decrease/eliminate the waste, improve the product durability, achieve better health and safety conditions, and enhance the system and processes overall performance). Regarding the research gap, the needs and implementation techniques of the sustainable manufacturing still need to be implemented in an effective way. Thus, a detailed guideline to define the concepts and practice techniques of the sustainable manufacturing is required. In addition, developing artificial intelligence-based methods can effectively support achieving sustainable manufacturing concepts in all levels (i.e., system, process, and product). Furthermore, it is necessary to keep developing the current sustainable technologies (see Table 1) to achieve more benefits towards a sustainable manufacturing environment.

8. Summary

In this work, a review study that discusses the sustainable manufacturing approach is presented in terms of concepts, implementation techniques, and assessment methods. The interaction among the three sustainable levels (i.e., process, product, and system) provides the required sustainable target. The main expectations of building a sustainable manufacturing system are the following: to reduce the energy consumption, minimize the waste, improve the product durability, decrease the environmental and health concerns, enhance the quality of the product, and develop renewable energy resources. To accomplish these objectives, several needs (e.g., approach, methods, data, research, and integration) are required. Additionally, the implementation of the sustainable manufacturing approach requires employing several design aspects. These aspects are as follows: design for environmental impact, design for resource utilization and economy, design for manufacturability, design for functionality, and design for social impact. Furthermore, five main stages are required to successfully achieve an effective sustainable system. These stages include the following: developing work practice and maintenance, process optimization, raw material substitution, employing new technologies, and developing new product designs. Once the implementation stages are defined, it is also necessary to have a solid assessment model in order to evaluate the sustainability of manufacturing systems. It is obtained from the open literature that five major elements are mainly used to assess the sustainability aspects of the manufacturing systems. These elements are as follows: manufacturing costs, energy consumption, environmental impact, waste management, and personal health and safety. The integration and analysis of all sustainable elements provides the optimal operating levels, from a sustainability perspective.

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