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Material efficiency: a key sustainable manufacturing strategy

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Material efficiency: a key sustainable manufacturing strategy

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Abstract. Inefficient material utilization results in extra pressure on the environment for the extraction of more material to meet production demand and therefore makes the environment unsustainable. The survival of the manufacturing industry depends on its ability to balance several requirements to meet up with dynamic market demand particularly materials for production ranging from raw materials, intermediate materials to spare components for maintenance. In the past, sustainability and efficiency were no challenges to the manufacturers and material extraction from the environment was always below replenishment. Presently, the reverse is the case where the demand for production material has become incessant and surpasses supply on account of increasing population and modern manufacturing practices thereby resulting in irresponsible exploitation of raw material. This paper aims to evaluate the current efforts in the topic area to gain insight into the impact of material efficiency on the manufacturing performance concerning other manufacturing strategies alongside the environment. It appears from the review that the balance between manufacturing material extraction from the environment and the replenishment rate determines the sustainability of both the manufacturing system and the environment. Hence material efficiency is an index for sustainable manufacturing strategy. We recommend the future research direction to looks into the development and determination of balance between manufacturing material extraction from the environment and the replenishment rate for a sustainable future manufacturing.

Keywords: Material, efficiency, sustainable, manufacturing, strategy, and environment

1. Introduction

Sustainable consumption and production is one of the sustainable development goals drafted by the United Nations for the year 2030 and it addresses the current impact of manufacturing on the planet and provides future directions for manufacturing firms to manufacture goods more sustainably. The urgent call for action on the implementation of sustainable consumption and production (SCP) within the manufacturing sector can be attributed to the negative impact of the sector on the planet. An increase in material use can be linked to the increase in the standard of living of an ever-growing population, therefore with the ever-increasing demands of consumers producers have to rise to the challenge by using up more resources. Sustainable manufacturing is closely related to SCP in terms of goals since they both address the triple bottom line of people, planet, and profit. Sustainable manufacturing anchors on the three broad dimensions i.e. environment, economy, and society although some authors have included others such as technology, efficiency, etc., however, these three are the most prevalent in literature. Sustainable manufacturing can, therefore, be defined as a process of creating value by manufacturing goods in a way that is environmentally friendly, economically sound, and have a positive impact on the society.

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Material efficiency in the manufacturing sector is key and central to other sustainable manufacturing strategies however sparse literature in this field shows a lack of understanding of this concept. The most discussed sustainable manufacturing strategy is energy efficiency and this due to the issue of global warming and climate change, also the legislative laws and fines placed by governments and other institutions around the globe make an integral part of most manufacturing firms, meanwhile little attention is given to material efficiency. Although an increase in energy efficiency can lead to the reduction of material usage, however energy efficiency has peaked in terms of innovation and renewable energy is not as efficient as fossil fuel or natural gas therefore its application in large scale manufacturing firms is limited. Material efficiency can be defined as the percentage of material used in manufacturing a product, i.e. the conversion of material into a finished product. Implementing this key strategy would have a direct impact on the environmental dimension of sustainable manufacturing which also reflects directly on the other two major dimensions. An increase in material efficiency will have a positive impact on energy usage within the plant, water usage, waste produced, emission, and CO_2 footprint.

2. Literature review

The manufacturing firms are typically profit-oriented and therefore do not consider the effect of their manufacturing activities on the immediate environment, however, there's been a major shift in manufacturing since the inception of our common future summit held in Brundtland 1987 and also growing concerns about global warming, several laws have been implemented in various nations to ensure manufacturing firms comply. At the summit sustainable development was defined as "the ability of the present generation to meet its need without compromising the ability of the future generation to meet theirs". Therefore sustainable manufacturing can the defined as the ability of manufacturing firms to meet the needs of the present generation without tampering with the ability of the future manufacturing firms to provide for the needs of the future generation.

According to [13] 63.40% of sustainable manufacturing studies are carried out in developed countries where the laws are strictly enforced, manufacturers began to look for ways to meet the minimum acceptable requirement on environmental discharge and at the same time maintain their market share. However, food manufacturing, steel, and chemical industries have the least active participation in sustainable manufacturing. Maintaining market share while meeting stipulated government requirements for manufacturing activities made production efficiency an integral aspect of these firms. Several strategies have been employed by the different organization as the nature of their activities differ from one another, this makes it impossible to have a generic sustainable framework or strategy to address all manufacturing industries, however, an industry-specific framework can be adopted in same manufacturing since firm in that particular industry have similar manufacturing processes.

2.1 Sustainable Manufacturing Strategies

The successful implementation of sustainable manufacturing in any manufacturing firm anchors on implementing the strategies that will lead to an increase in efficiency, however identifying these strategies can be challenging, but a clear understanding of the operational process will give clear directions on what strategies would be most effective when implemented. Several studies have been carried out on sustainable manufacturing strategies, for instance [19] proposed the use of three sustainable manufacturing strategies namely, material, energy, and waste (MEW) to address environmental performance within a manufacturing plant, MEW is a process flow modeling approach. Data generated from a case facility was analyzed on a spreadsheet model according to the MEW process flow. This approach led to the discovery and selection of key improvement areas in the environmental dimension of sustainable manufacturing. Similarly, a MEW process flow modeling was implemented by [5], a collective effort from manufacturing industries, academia, and software developing company made this research comprehensive as MEW

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process flow modeling and sustainable building design were consolidated with the aid of a developed modeling, simulation, and analysis tool. This tool-assisted in designing and creating an improvement plan for a sustainable manufacturing plant.

[6] carried out a comprehensive study on sustainable manufacturing highlighting the three major dimensions of sustainability, and sub-dimensions which are often referred to as strategies in the existing literature. Other dimensions aside from the three main dimensions of sustainability were also identified in this research, which implied that manufacturing firms are to apply sustainable strategies that are suitable and specific for the firm. The authors observed that out of the three main dimensions of sustainability, the environmental dimension received more attention therefore formal concept analysis (FCA) was used to further analyze the choice of manufacturers in selecting and combining different strategies within the environmental dimension to achieve sustainability.

Table 1. Reference of Sustainable Manufacturing Strategies: Environmental Dimension

Sustainable Manufacturing Strategies	Strategy Goal	Author
Energy efficiency	(i) Minimize energy and material usage (ii) Improve production efficiency (iii) Minimize carbon footprint and emission.	[11], [6], [14], [15].
Waste minimization	(i) Minimize waste and pollution (ii) Improve production efficiency (iii) Cost reduction (iv) Minimize usage of virgin raw materials	[3], [6], [21], [20], [16].
Water Usage	(i) Minimize the quantity of water used during production (i) Increase the availability of clean water	[6], [23], [4].
Material efficiency	(i) Utilize material and energy efficiently (ii) Improve production efficiency (iii) Minimize waste and pollution (iv) Recycling	[17], [6], [14], [20], [16].
Resource efficiency	(i) Utilize resources (material, energy) efficiently (ii) Minimize waste and pollution (iii) Minimize the extraction of virgin raw material (iv) Improve Earth replenishment rate	[7], [14], [23], [16].

Table 1 Cont'd

Sustainable Manufacturing Strategies	Strategy Goal	Author
Eco-efficiency	(i) Utilize resources efficiently (ii) Minimize waste and pollution (iii) Improve the quality of life (iv) Improve earth carrying capacity	[14], [2], [1], [16].
Carbon footprint	(i) Minimize emission of CO_2 (ii) Improve the quality of air	[6], [14], [15].
Emission	(i) Meet the standard requirement for emission of gases (ii) Improve the quality of air	[6], [14], [15].
Transport	(i) Improve supply chain and logistics (ii) Reduce Emission and carbon footprint	[6], [14].
Landfill	(i) Eliminate and reduce waste	[6]
Biodiversity	(i) Improve Earth replenishment rate (ii) Improve the quality of life	[6]

Table 1 illustrates references of key sustainable manufacturing strategies concerning the environment indicating the strategy to the environment. It suggests that the environment must be preserved while manufacturing activities continue. This implies that Hence, there is a need for balance between manufacturing material extraction from the environment and replenishment rate for sustainable manufacturing system and environment

Water, material, carbon footprint, emissions, transport, biodiversity, resource, energy, waste, and landfill were identified to be the main strategies in this research and results show that energy, waste, and emissions were the most discussed in the literature with material coming in at the fourth position. On the other hand [9] stated that implementation of three dimensions of sustainability, not just the environmental aspect is essential to achieve the aim of sustainable manufacturing. The study analyzes a comprehensive index of sustainability which includes several performance indices. This reasearch aimed to create an effective framework to investigate the present condition of manufacturing industries by combining environmental, social, economic, and manufacturing variables. The proposal has its origins in patterns and limitations observed in the manufacturing industry sustainability literature and it is built on the framework of the analytical hierarchy process (AHP). A list of metrics is proposed, based on an AHP scoring system, assessing the industry performance. The next steps include grouping industries across the four dimensions according to common deficiencies and developing a framework for cooperation.

2.2. Material Efficiency: A Key Sustainable Strategy

Increasing material efficiency leads to reducing both the amount of industrial waste and the use of energy. Nevertheless, there was less reported describing what to calculate in a manufacturing firm for material efficiency. This paper reviews the recent practice of performance metrics for material efficiency in a manufacturing context using a bottom-up approach. In addition to the research study, empirical evidence was gathered from seven major manufacturing firms in Sweden via a multiple case study. The findings suggest that current metrics of material efficiency are constrained and are mainly calculated as criteria of cost or quality rather than the environment. The limited number of metrics contribute to the fact that material efficiency is not recognized as a core activity in manufacturing firms and is handled by the environment department with little operational connection [18].

[8] stated that with abundant research studies on material flow and a growing understanding of the need for economic dematerialization, manufacturing firms have often failed to take advantage of the many opportunities to increase materials efficiency. The potential solution provided in this article is material management services provided by external suppliers. This also provides a theoretical framework for analyzing various eco-efficient service business models and expands the definition of material management services. [17] affirmed that measures in material efficiency, such as recycling rates and dematerialization are also used to create sustainable development goals to achieve higher resource efficiency and less impact on the environment. The study carried out by [17] aimed to identify appropriate metrics of material efficiency to identify the sustainability impact of waste and recycling programs that leverage PET bottle waste management in three European countries with different waste management mechanisms and success rates. Material flow analysis in conjunction with life cycle analysis was carried out to examine the connection between the two dimensions of the material efficiency and environmental influence of each system. The production of PET bottles in Germany, Austria, and Serbia was 6.0 kg/person in the year 2017, and 5.4 kg/person in the 2013 and 6.9 kg/person in the year 2015 respectively. Meanwhile, the PET recycling rate of this waste flow in Germany, Austria, and Serbia is 91%, 41%, and 11% respectively. Increased material efficiency resulted in higher environmental performance.

Comprehensive research on the Finnish National Waste Plan, research, was carried out between 2007 and 2016. This research aimed to apply alternative concepts of waste avoidance or material efficiency and the transition from waste avoidance to material efficiency. The advantages and drawbacks of these complementary principles have been evaluated using parameters such as semantic dimensions, synergy legal aspects, and tracking applicability [12]. One potential aspect of a sustainable manufacturing strategy is the efficient use of materials. [16] reviewed existing studies on sustainable manufacturing strategies that include performance improvement in materials. Four key strategies used in this research are material efficiency, waste minimization, eco-efficiency, and resource efficiency. The research was analyzed to identify the main characteristic features of these sustainable manufacturing strategies and 17 features were found. Afterward, the four approaches were compared to all the features and contrasted. Although existing literature uses these sustainable manufacturing strategy terms frequently in a confusing, sometimes interchangeable way, this study executed by [16] however established an explicit distinction between them. Definition, scope, and applicability of measurement were revealed to be key features affecting the ability of manufacturing companies to implement the recommended strategy effectively. It was noted that the most implementable strategies do not necessarily have to contain all the dimensions for manufacturers interested in being more sustainable, this however creates a challenge between ease of execution of strategies and level of impact.

Material efficiency is a fundamental component of modern thinking to respond to the dilemma of minimizing the environmental impacts of manufacturing firms and resource depletion while meeting the demands of materials for service and functionality. The definition of the circular economy, which is built on the idea of maximizing the value contained in resources and goods through the life cycle, is directly related to material efficiency. Even though materials such as steel are among the most 'circular' of produced materials due to high end-of-life recycling rates, there are substantial prospects for better material efficiency, which also needs to be extensively implemented. Life Cycle Assessment is usually utilized to evaluate the environmental advantages of reclaiming and recycling materials through the supply chain of manufactured products and at the end of life. Using an analogy obtained from renewable energy production, this study investigated the relationship between the lifecycle of a product and the environmental case for implemented strategies used to increase material efficiency [22]. Similarly, [10] discussed the material efficiency of aluminum scrap during production. Due to production failure some materials in this case aluminum scraps are usually rejected at the end of a production process, however, the amount of scarp produced by one of the aluminum smelting furnaces in the reduction pot manufacturing process exceeds the accepted standard of 5 to 10 percent. Automatically this harms the final output of the manufacturing process. This study implemented the use of lean manufacturing practices and six sigma tools to increase material efficiency results in a 6% decrease in the amount of aluminum scrap resulted in increased final output or products.

The link between material efficiency and other sustainable manufacturing strategies can be seen as an increase in material efficiency will result to increase in energy efficiency [19], prevention and minimization of waste [12], effective resource efficiency [16], reduced transportation trips of virgin raw materials which also reduces emission contributed and the CO_2 footprint, reduced emission at the operational level as equipment consume less energy which in return leads to reduced emission, the drastic reduction of waste flow to the landfill and the associated cost of transporting the waste [3], [6], [18]. However, these are a few impact material efficiency has on other manufacturing strategies.

3. Conclusion

The implementation of material efficiency as an index for sustainable manufacturing strategy can help achieve other sustainable manufacturing strategies. Although energy efficiency received the most attention of researchers in existing literature, material efficiency is encompassing and its implementation can assist in achieving sustainable manufacturing strategy. It appears that the balance between manufacturing material extraction from the environment and the replenishment rate determines the sustainability of the manufacturing system and the environment. Hence material efficiency is an index for sustainable manufacturing strategy

4. Recommendation

We recommend that the future research direction to looks into the development and determination of balance between manufacturing material extraction from the environment and replenishment rate for a sustainable manufacturing environment.

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