Sustainable Manufacturing Assessment: Approach and the Trend Towards Life Cycle Sustainability Analysis

Mijoh GBEDEDO[a,1] and Kapila LIYANAGE[b]
College of Engineering and Technology, University of Derby, United Kingdom
[a]*m.gbededo@derby.ac.uk* [b]*k.liyanage@derby.ac.uk*

Abstract. Recently, Life Cycle Sustainability Assessment framework has been launched for experts from different disciplinary fields to discuss and develop a holistic and integrated approach that supports effective sustainability decisions. Many authors have used different and combination of methodologies in support of this goal; some authors focus on competitive manufacturing with integrated environmental protection elements, some focus on energy and resource efficient technologies and eco-designs while other authors underscored the importance of holistic assessment of the three sustainability factors to drive effective sustainable manufacturing. However, it is evidence from the research that the existing approaches lack holistic and analytical approach that consolidates the objectives of other sustainable product development methods. This paper used a structured approach to a literature review to systematically examine sustainable manufacturing approach and the move from segmented assessment methods to the holistic and integrated Life Cycle Sustainability Analysis, and identify gaps both in practice and research within the manufacturing industry domain. In view of the result, the research proposed a framework that integrates goals that support progressive sustainable product development with methods that focus on the holistic quantitative analysis of the manufacturing production process.

Keywords. Sustainability, Manufacturing, Life Cycle Sustainability Analysis

1. Introduction

The challenges involved in extracting and transforming raw materials into consumers' product are enormous, and the implications of the associated activities are currently placing a great demand and additional responsibilities on the manufacturing industries. It has been established in many research that manufacturing activities are causing alarming degradation to the planet natural resources and generating harmful effects on the general society [1]-[3]. The advent of Brundtland report tagged "Our Common Future", has also sparked a new trend and the need to evaluate the performance of industries towards "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs" [4]. The report has been interpreted to anchor on three sustainability dimensions: economic development, social development and environmental protection [5]-[7]. Since the adoption of this report by

[1] Mijoh A. Gbededo, College of Engineering and Technology, University of Derby, Markeaton Street, DE22 3AW Derby, United Kingdom; E-mail: m.gbededo@derby.ac.uk..

the international bodies, regulatory and legislative pressures on the manufacturing industries have increased, and there are growing changes in the consumers' demand patterns for sustainable products and practices [2], [8], [9]. Thus the current global focus is on supporting and coercing manufacturing industries to implement efficient production practices that enable development of products and services with reduced negative environmental and societal impacts [10], [11]. The need for manufacturing industries to embark on sustainable product development and the use of assessment methodologies to support decision-making, therefore, became apparent. However, the inability to simultaneously assess the three sustainability factors placed constraints on effective sustainable manufacturing decisions [12], [13]. Although there are contemporary quantitative assessment frameworks capable of addressing and assessing the combination of one or two of the sustainability factors [14]-[16], the frameworks have neither adequately integrated all the three factors nor considered the effects of their interdependence, and the dynamism involves in the manufacturing production process.

In 2011, United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) [17], under its Life Cycle Initiative programme, published a framework to support the development of a holistic Life Cycle Sustainability Assessment (LCSA). The framework provides the stage for a new approach to sustainability subject among the scientists, researchers and practitioners to discuss and implement sustainable development with a holistic life cycle perspective [7], [18], [19]. The objectives of this research are, therefore, to examine within the manufacturing industries, different approach towards sustainable manufacturing and the direction and the trend from an individual or segmented assessment methods to an integrated holistic assessment of the sustainability factors, and to study and identify gaps both in practice and research within the manufacturing industry. This research also identified and proposed a framework that integrates goals that support progressive sustainable product development with methods that focus on the holistic quantitative analysis of the manufacturing process.

2. Research Methodology

This research adopts a structured approach to full literature review based on defined research question, goals and scope [20]-[26]. In respect of the research question, this review focuses on what are the approach to sustainable manufacturing, and to what extent are the approaches being moved from segmented assessment methods to the holistic and integrated Life Cycle Sustainability Analysis (LCSA). The goal is to identify gaps both in practice and research within the boundary of gate-to-gate manufacturing production domain. The scope is limited to the production process and the literature published between 2006 and 2015 (inclusive) on approach to sustainable manufacturing. The purpose is to focus on the most previous and up to date methodologies after UNEP/SETAC launched the LCSA framework in 2011 [17]. The delimited manufacturing production domain is to allow focus on methodologies adopted for assessment of a discrete manufacturing production process for a sustainable product under design. The search, sort and eliminate data collection strategy adopted is depicted in Figure 1. A combination of keywords and wildcards were used to search for relevant articles in the major bibliographical database such as Web of Science (WOS), the University Library Catalogue, ScienceDirect, and GoogleScolar.

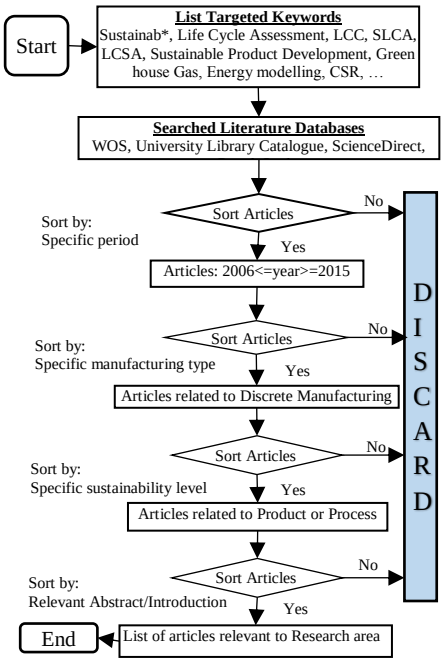

Figure 1. Search, Sort and Elimination Data Collection Technique

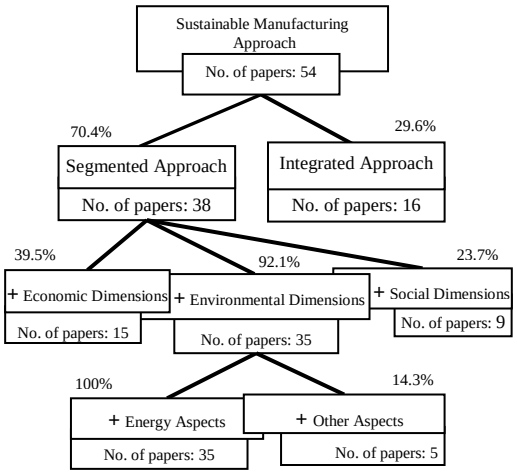

Figure 2. Classification of the Focuses of Sustainable Manufacturing Assessment

The listed relevant literature from the data collection process was then imported into an analytical framework for analysis and synthesis. A thematic synthesis as used by [21] was adopted due to its effectiveness in classifying and structuring reoccurring themes as depicted in Figure 2.

3. Result and Discussion

The data collection process produced a total of 54 literature relevant to the approach to sustainable manufacturing within the defined goal and scope. The data analysis of the literature shows, 38 (70.4%) of the papers focused on the segmented approach to sustainable manufacturing while 16 (29.6%) incorporated the three sustainability dimensions in their approach. Of the 38 segmented approaches, 92.1.3% included environmental, 39.5% included economic and 23.7% included social aspects with either of the other factors in their assessments. Further, the analysis shows that all (100%) of the approaches that included environmental factor concentrate on the energy aspect and 14.3% focused on materials or other aspects that related to environmental dimension (see Figure 2 above). The result reveals the imbalance of the approaches towards the three sustainability factors with a greater neglect for the importance of the social factor and its influence on other factors. It also shows the fact that the current sustainable manufacturing approaches tend to focus more on the competitive manufacturing that integrates environmental protection elements. The trend of the approaches to integrated sustainable manufacturing was also examined from 2006 to 2015, it was observed that the number of articles in this area increased after the launch of LCSA in 2011 [17], however, there was a fall after the peak in 2013 (Figure 3).

Years	Number of Articles	
	Segmented	Integrated
2006	1	1
2007	2	0
2008	3	1
2009	2	0
2010	10	3
2011	5	2
2012	4	2
2013	5	5
2014	3	1
2015	3	1
2016	0	0
Total	38	16
Percentage	70.37%	29.63%

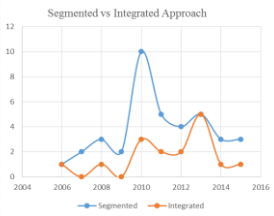

Figure 3. The trend of Approach to sustainable Manufacturing Between 2005 and 2016

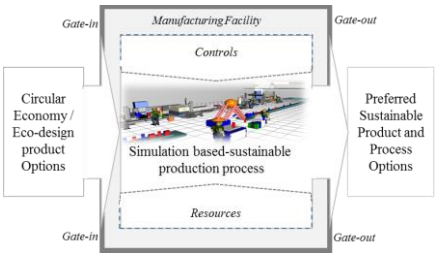

Figure 4. A Concept Diagram of Simulation-Based Impact Analysis of Sustainable Product Design

3.1. Challenges with Existing Sustainability Assessment Approach

Though the principles of LCA have been applied in various articles [5]-[7], [16], [18], [23], there is an agreed notion among the researchers of the complexity of the framework, the challenges and the time required to collect an inventory of a product life cycle which makes the framework almost impracticable [12], [19, [30]. Many researchers and practitioners have combined LCA principles with other methods for assessment of products sustainability [15], [18], [19], [27], [28]. However, the holistic performance of the products and comparison to alternative products design, or previous versions have not been thoroughly assessed due to difficulties in integrating all the sustainability aspects of the assessment processes [29], [30]. A holistic sustainability performance assessment incorporates the three sustainability dimensions in the assessment processes, and aggregate sustainability performance of all the actors in a product life cycle to inform the product designers for effective decision making [12]-[15]. According to Hutchins and Sutherland [13], sustainability is appreciated when the interdependencies of the three sustainability factors are considered [7], [18], [19], [31], [32]. The authors further posited that it is necessary to characterise the connection and interactions among the three sustainability factors before we can achieve sustainable development.

3.2. Aligning Energy Efficiency Approach to Sustainable Manufacturing

The importance of energy efficiency in the manufacturing production process is underscored in all the reviewed articles. The result shows that 100% of the approaches concentrate on the energy aspect. Methods such as Energy modelling, eco-design, Lean-green, and Energy Management Systems [1]-[3], [8], [9], [11], [16], [21] are examples of strategies adopted in an Eco-Efficient production system that aims at reducing environmental impacts and cost of production [1], [2], [7]-[9], [18]. Circular Economy (CE) has also emerged to describe an approach that combines various design techniques under eco-design mechanism with the aim of reducing the rate of consumption of natural resources through product lifespan extension and feasible economic case [25], [33], [34]. The main question is, however, how sustainable are the production processes involved in manufacturing the eco-innovative products? How do we assess their impacts on the economic, environment and society in order to drive effective sustainability decision?

A sustainable product, according to this research, is a product that is created using an eco-efficient manufacturing production process, conserves natural resources, eco-efficient in the use phase, competitive, safe and promotes social values and amenities for the workers and communities. Although there exist a significant positive relationship

between the eco-innovated products and sustainable products [3], [4], [6], there is need to align the manufacturing process of the products with a holistic view of sustainable development [4]. This research proposes an integrated methodology for impact analysis of the production process that enables assessment of the three sustainability factors (economic, social and environmental) in a dynamic production environment [30]. A simplified concept diagram of the proposed simulation-based impact analysis for a circular economy or eco-design product is depicted in Figure 4. The approach is to enable simulation and sustainability analysis of a proposed sustainable product design under various manufacturing control and resources in order to optimise and evaluate the manufacturing processes for the best competitive, sustainable process and product design.

4. Conclusion

This study examined the approach to sustainable manufacturing assessment, the trend towards LCSA and classified the focuses of sustainability assessments. The result shows that most of the approach lacks holistic view and LCSA is still in the immature stage. Most of the authors focus on competitive manufacturing integrated with environmentally sustainable innovations, while other authors underscored the importance of holistic assessment of the three sustainability factors. As posited by many authors, sustainable development is achievable when the connection and interactions among the three sustainability factors are considered [7], [13], [18], [19]. It should be noted that the current approaches to sustainable manufacturing that integrates the three factors in their assessments do not consider the interdependency of all the factors. The approaches still use the traditional individual assessment methods and summing up their results. According to research, this approach does not support effective decision-making and are prone to unintended negative consequences [7],[19],[32] hence, it is a clear gap for research on the issues of the influence of one sustainability factor on the other especially, when assessing the sustainability of a process or product under design. Another obvious gap in the current research is the challenge of aggregating and translating various social aspects from qualitative to quantitative weighted values and the study of their influence on and interdependencies with the economic and environmental factors.

With the aim of the holistic analysis of the three sustainability factors [7], [32]and overcoming the data collection complexity of a product life cycle, this research proposes a gate-to-gate analytical framework that combines existing approaches and enables effective assessment of the factors and decision-making for sustainable manufacturing.

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