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Total Life Cycle Sustainability Analysis of Additively Manufactured Products

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Abstract

Additive Manufacturing (AM) has become an enticing and rapidly growing manufacturing method for the production of components due to its unique advantages over conventional manufacturing (CM), including complex geometric capabilities and functional features. Sustainability concerns for AM products are still among the major technological challenges. A holistic sustainability analysis of such products covering the entire life cycle is lacking in the current literature. This paper presents the total life cycle sustainability analysis of AM products, through the recently established Product Sustainability Index (*ProdSI*) framework. A case study is presented with two iterations of AM product validating the *ProdSI* metrics for AM products.

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Keywords: Product sustainability; Product Sustainability Index (*ProdSI*); Additive Manufacturing; Total Life Cycle; Sustainable Manufacturing

1. Introduction

In recent times, sustainability concerns in all facets of human life have become a major issue due to the limited and often depleting resources, ever-increasing global population with rapidly growing societal needs, with prevailing social and economic disparities among communities and nations. Manufacturing being a major pillar of development, and is generally known to be the engine for wealth generation. Therefore, it is very important to focus on achieving sustainability in manufacturing. Manufacturing sustainability must also consider Triple Bottom Line – TBL concerns [1] (economic, environmental and societal) at the three intertwined elements of manufacturing - products, process and system levels [2].

The need for adopting suitable product sustainability evaluation methods rise from the societal demand for preferably identifying and promoting sustainable products. Four main life cycle stages (Pre-manufacture, Manufacture, Use and Post-use) of products may have different impacts on the overall product sustainability. Therefore, complete understanding of sustainability content of a manufactured product can only be reached through a comprehensive analysis of the total life cycle of the product, which takes all four stages of product in to account simultaneously. Thus, it is imperative that any new evaluation method for product sustainability must incorporate the total life cycle view.

With the unique and novel capabilities that additive manufacturing brings in, there is an increasing focus in the industry to develop and include metals and composite materials in Additive Manufacturing (AM) of their functionally superior products/components. There rises the need to understand the impact of AM on a product's sustainability, compared to Conventional Manufacturing (CM). The following sections discuss, the impact of AM on sustainability visible through all four stages of product's life cycle, reiterating the need of total life cycle analysis.

When considering AM during design of a product, in most cases only certain components of the product will be additively manufactured. Previous literature [3] presents the selection of most suitable components for AM as one of the key factors in improving the overall product's sustainability. Although there is considerable amount of literature on AM, work done on sustainability evaluation of such products is still

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lacking. As such, this paper presents the results of a preliminary study on this important aspect, with a case study to evaluate the sustainability of an additively manufactured component. The recently established Product Sustainability Index (*ProdSI*) [4] method is used as it provides a comprehensive framework to measure the impacts of all relevant metrics of product sustainability during all four life cycle stages of a product. While the *ProdSI* method has been used in in the past work with case studies involving CM products, this paper presents the first attempt being made to study AM products. Hence unique and specific concerns discussed in the following section must be noted when defining the *ProdSI* metrics for AM products.

2. Unique sustainability concerns in manufacturing of AM products

When selecting a manufacturing process for a product, the primary concerns for a design/manufacturing engineer are production quantity, design complexity and functional/material requirements of the product. At present, as Fig. 1 shows sustainability content of the product has become a consequence of the decisions taken depending on these primary concerns. To establish sustainability as a major design concern, the impacts of individual design decisions on total life cycle sustainability must be considered upfront during early design stage.

Fig. 1 Product sustainability impacts of major product design decisions: current and proposed methods

Although discussion on making sustainability a major design decision is beyond the scope of this paper, its importance is highlighted throughout the discussion related to considering AM as a manufacturing option. Impacts of production quantity, complexity and functional/material requirements on the suitability, or not, of AM is discussed below.

Compared to CM, currently AM processes have longer processing times due to the layer by layer nature of the product fabrication process, leading to lower production rates. But certain complex designs may take even longer processing times if CM processes used, due to the need for multiple process steps or simply being unable to produce due to manufacturing limitations. As previous literature [5] states, in some sense with AM processes the 'complexity is free', i.e., the level of complexity of a product's design does not necessarily increase the cost of production. This work [5] also introduces a 3-axis model, including product complexity, customization level and volume/quantity. Yet during this work, along with product complexity and quantity, functional/material requirements aspect was found to be more inclusive than considering only customization requirements. A previous work [3] suggests a framework to evaluate subjective measurements such as design complexity, speed and accuracy of AM processes.

Furthermore, if a product has functional requirements with high level of product-to-product customization (e.g., biomedical applications), AM can be better in both economic and environmental senses due to avoidance of product-specific tooling. The use of standard equipment also enables facility-sharing and formation of joint consortia as discussed in previous literature [6].

Depending on functional requirements, AM enables features to be integrated and help eliminate additional components to streamline the designs by improving sustainability through material and weight savings. Previous literature [7, 8] also discusses the process of identification of components to be additively manufactured and the impact of redesign of adjacent components for optimizing the product design for functionality.

As these decisions are to be taken at an early stage of product's life cycle, there must be a decision support tool to help expose sustainability concerns and guide the designers towards most sustainable options. Therefore, future work will be carried out to suggest a progressive product sustainability content analysis method for the early stages of design as a decision support tool, which can complement the more holistic evaluation method (i.e., *ProdSI*) to be used beyond the final stages of product development as seen in Fig. 2.

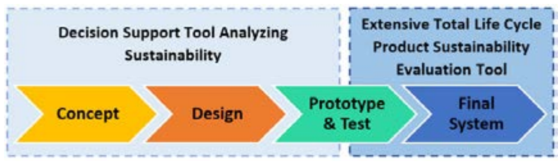

Fig. 2 Progressive product sustainability analysis framework to support design for sustainability

2.1. Quality

Quality requirements of a product are specified based on the functional requirements of the product and customer expectations. Since product sustainability requires improving or maintaining quality (which has direct impact on Use stage of product's life cycle), following concerns due to AM process limitations were identified as important metrics. Depending on the application and part specifications, these metrics must be included in the product sustainability evaluation criteria.

Surface quality of AM products is found to be a concern due to the 'ridge effect' caused by layering and the build orientation effect [9, 10]. Improvements are suggested by