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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.

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.

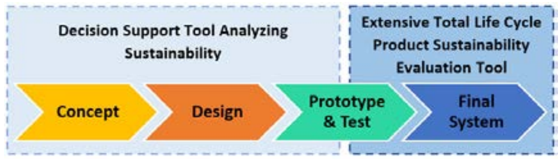

Fig. 2 Progressive product sustainability analysis framework to support design for sustainability

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 taking finer deposition layer thickness in AM, but at the cost of considerable increase of production time. The common alternative is secondary finish machining on functional surfaces, allowing surface quality comparable to conventional processes. Sustainability analysis must therefore also take post processes' sustainability impact into account.

Metal AM products' mechanical properties (such as stress-strain, ductility, fatigue properties and microstructure) have been studied extensively in the literature [9, 11, 12], and have been found to exhibit more directional properties compared to CM parts. The work further explains the use of post heat-treatment processes to improve the mechanical properties to a level comparable to, or better than the CM parts. Thus, understanding the sustainability impact of post-processes becomes extremely important.

3. Product Sustainability Index (*ProdSI*) method

Recent work [13] proposed a new *ProdSI* methodology for comprehensive assessment of product sustainability. Shuaib et al. [4] comprehensively reviewed the state-of-art in product sustainability evaluation methods, and identified the *ProdSI* method to be a more exhaustive method than all previously established methods due to its consideration of all four product life cycle stages to enable total sustainability evaluation, and the earlier work on *6R* principles (reduce, reuse, recycle, recover, redesign, and remanufacture) [14].

The *ProdSI* method uses a five-step hierarchical process bottom to top as: individual metrics, sub-clusters, clusters, sub-indices (based on TBL) and ultimately the *ProdSI* value (as shown in Fig. 3). Assessment is done using bottom-up procedure, starting with metric measurements of each product, then normalizing the measurements to enable aggregation with different types of measurements. Normalized data is given weightage depending on their relative importance to sustainability, and then aggregated into sub-clusters. Sub-cluster data is again given a weightage factor depending on relative importance and aggregated to cluster level, which are then given cluster weightage factors and aggregated into the three sub-indices. The three sub-indices of Economy, Environment and Society are given a weightage factor of 1/3 each, and the data is then aggregated to obtain the final *ProdSI* score for each product/component.

3.1. Selection of metrics

In addition to the metrics directly specified in the *ProdSI* method, number of metrics in the framework are set as product-specific. During the case study presented in this paper, relevant metrics were carefully selected to provide a focus on the impact of sustainability due to AM and CM processes.

3.2. Normalization

Normalization of different metric values was done similar to the previous work [15]. Different metric values were normalized to a scale of 1 to 10, where 1 being the least sustainable and 10 being the most sustainable option.

Fig. 3 *ProdSI* sub-indices and clusters

3.3. Weightage and aggregation

Aggregation of weighted metrics across sub-clusters, clusters and sub-indices to ultimately obtain the *ProdSI* value was carried out similar to the previously established procedure [13, 16].

$$ProdSI = \frac{1}{3}(Ec + Ev + Sc)$$

$$ProdSI = \frac{1}{3}(\sum_{i=1}^{3} w_i^c C_i + \sum_{i=4}^{8} w_i^c C_i + \sum_{i=9}^{13} w_i^c C_i$$

$$C_m = \sum SC_j w_j^{sc} \;\; \forall j$$

$$SC_n = \sum M_k w_k^m \;\; \forall j$$

Ec - Sub-index score for economic impact
Ev - Sub-index score for environmental impact
So - Sub-index score for societal impact
w_i^c - Weighting factor for the i-th cluster
w_j^{sc} - Weighting factor for the j-th sub-cluster
w_k^m - Weighting factor for the k-th metric
C_m - Score for m-th cluster
SC_n - Score for the n-th sub-cluster
M_k - Score for the k-th metric

4. Case study: Application of *ProdSI* for AM

A case study was conducted at component level to identify the sustainability content of different component variations, and explore if additive manufacturing can be a more sustainable alternative to conventional manufacturing process.

4.1. Components selected for the case study

A mechanical component used in a consumer electronics product's internal lever mechanism was identified as a potential candidate for the case study. A simplified version

(Flat design shown in Fig. 4) of the component was designed for ease of fabricating using CM methods. The component in the prototype product as seen in the Fig. 5 has 3-dimensional (3D) complex features. It is currently made using metal additive manufacturing processes for prototyping purposes.

The case study analysis was done on four component variations (part made for prototype product and 3 fictional variations). The simplified flat 2-dimensional (2D) design was taken as the base design (Fig. 4). The version *P1-CM* was the variation made using conventional manufacturing methods (forging); *P1-AM* was the additively manufactured (with finish machining) version of the same flat design as *P1-CM.*

The prototype's component design was taken as the 2nd design, which has complex 3D features for integrated functionality. The 3D version made using conventional manufacturing methods (forging and machining) was identified as *P2-CM*. The actual component from the prototype product, additively made (with finish machining) in 3D was identified as *P2-AM.*

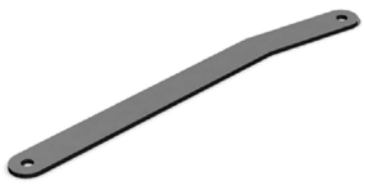

Fig. 4 Basic flat design (for parts *P1-CM* and *P1-AM*)

The basic function of the selected part is to act as a lever between two moving mechanisms. Hence, strength and rigidity of the product were two of the main concerns. For a given material type (Cobalt Chromium alloy *Co-30Cr-5Mo* was taken as it was the material of original component *P2-AM*), thickness is a major factor in structural rigidity. The rigidity requirement was satisfied in the advanced 3D design (*P2-CM* & *P2-AM*) using fluted/ridged-edges. This improved material utilization by having reduced center thickness compared to the basic flat design (*P1-CM* & *P1-AM*). The basic flat design lacked the 3D features present in advanced design. These features improved functionality of 3D design by integrating additional functions (such as spring mount attachment).

Fig. 5 Part from the prototype product (*P2-AM*)

Design complexity of *P1-CM* and *P1-AM* were the same and since they were flat (2D) in design, had a lower design complexity. In comparison, *P2-CM* and *P2-AM* had a higher design complexity due to the 3D design features.

For the case study, quantity requirement for each product variation was assumed to be 1000 units.

4.2. Product sustainability evaluation using ProdSI method

The four variations were analyzed by considering 38 individual metrics in the *ProdSI* framework developed. Metric level scores were given to each variation and subsequent scores were calculated at sub-cluster, cluster and sub-index levels using the earlier discussed normalization and weighted aggregation procedures leading to the ultimate *ProdSI* score for each variation. Due to space constraints, only a part of the developed metrics system is presented in Table 1.

Table 1. Portion of *ProdSI* evaluation for the case study

Final *ProdSI* Scores				Sub Index Level						Cluster Level					
				Sub Index	W_si Weight	Weighted Scores				Cluster	Wi_c Weight	Weighted Scores			
P1-CM	P1-AM	P2-CM	P2-AM			P1-CM	P1-AM	P2-CM	P2-AM			P1-CM	P1-AM	P2-CM	P2-AM
6.3	**5.6**	**4.4**	**5.7**	**Economy**	**0.33**	6.90	4.27	3.30	4.13	Initial investment	**0.33**	6.0	2.6	4.2	2.6
										Direct/indirect costs & overheads	**0.33**	5.3	6.2	2.5	5.2
										Benefits and losses	**0.33**	9.4	4.0	3.2	4.6
				Environment	**0.33**	5.56	7.03	3.64	6.82	Material use & Efficiency	**0.20**	5.0	8.7	1.3	8.0
										Energy use & efficiency	**0.20**	8.0	4.0	7.0	4.0
										Other resource.	**0.20**	5.0	9.0	3.0	9.0
										Wastes & emissions	**0.20**	4.8	6.5	2.7	6.3
										Product EOL	**0.20**	5.0	7.0	4.2	6.8
				Society	**0.33**	6.45	5.61	6.34	6.09	Product quality & durability	**0.30**	7.1	6.4	4.8	5.5
										Functional performance	**0.30**	5.4	5.3	7.8	8.2
										Prod. EOL management	**0.20**	8.0	3.0	8.0	3.0
										Product safety & health impact	**0.20**	5.5	7.5	4.8	6.9

5. Results and discussion

From Fig. 6 it is evident that *P1-CM* has a considerably higher score in Economy sub-index compared to the AM component *P1-AM* (higher scores indicate higher sustainability). This is expected, as costs related to AM are comparably higher due to higher capital costs involved along with considerably low production cost and higher production rate involved with CM of the basic 2D design. Since the Benefits and losses cluster includes metrics such as Sales price and Profit, *P1-CM* gains a higher advantage. As for the 3D design (*P2-CM* and *P2-AM*) where a complex integrated part may be a necessity, Fig. 6 shows there is only a minor difference in this sub-index. Mainly due to labor cost and material cost advantage, *P2-AM* scores better in terms of Direct/indirect costs and overheads cluster, enabling a better overall economy sub-index score compared to *P2-CM*. Since the 3D design would require precision machining, CM loses the edge in cost effectiveness in *P2-CM's* complex 3D design, which enabled *P1-CM* a considerable lead in the Benefits and losses cluster.

Environmental sub-index scores shown in Fig. 7 reflect a better overall performance in sub-clusters related to Material and resource use efficiency (which includes the metrics Total product material use and Material utilization), both AM components have better environmental sustainability performance. Especially in a case where a complex design is needed, *P2-AM* shows a considerably better environment sub-index score compared to *P2-CM* due to the high scrap material produced during CM's machining of intricate shapes of the 3D part. Mainly the Mass of water used metric was considered for Other resource use and efficiency cluster, which enabled AM components to score higher. If more details are available on other natural resources use during each manufacturing process, the scores will be changed. Wastes and emissions cluster (which considers metrics such as Mass of solid waste, Disposed hazardous liquid waste and Noise emissions) also helped improving Environment sub-index scores of AM components. AM products End-of-Life (EOL) is one area where more research needs to be done in order to understand true sustainability concerns. But, due to AM's capabilities/potential of repair and remanufacturing of components, the two AM components (*P1-AM* and *P2-AM*) scored slightly higher scores.

Society sub-index scores (Fig. 8) are fairly similar for all components selected. In the Functional performance cluster, both 2D components would perform similar, and both 3D components would also perform alike. In the individual metric Compliance with tolerances, the CM products generally scored better compared to AM components. On the other hand, more complex 3D designs earned better scores in Functional effectiveness and Ease of assembly metrics, due to their integrated functionalities. The CM variations' overall Society sub-index scores are slightly higher mainly due to better scores in the product End-of-Life management cluster, which mainly includes the metric Ease of EOL product recovery. As noted, this is an area where AM components lack specific data for proper evaluation. With continued research and broader applications in industry of AM products, more accurate sustainability evaluations would emerge in the future for quantitative comparisons with CM products. It is also expected that the active deployment of 6R principles involving product recovery, reuse and remanufacturing activities will naturally enforce the need for considering the EOL options far more rigorously and effectively with the overall life cycle benefits.

As shown in Table 1, in terms of the overall product sustainability scores, *P1-CM* has higher score (6.3) compared to the AM alternative *P1-AM* with score of 5.6. But, in an application, where complex 3D integrated design such as Part 2 is a necessity, this shows that the AM component (*P2-AM*) will be the more sustainable option (with higher *ProdSI* score of 5.7), compared to the CM alternative *P2-CM* (with the score of 4.4).

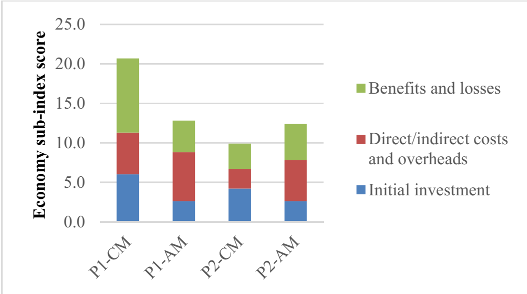

Fig. 6 Economy sub-index scores for each component

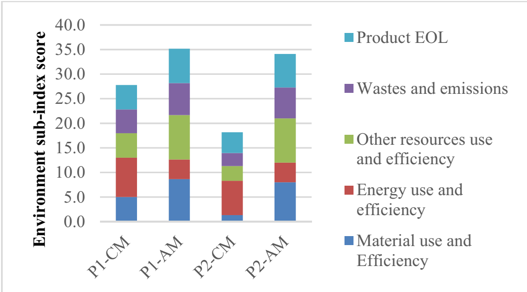

Fig. 7 Environment sub-index scores for each component

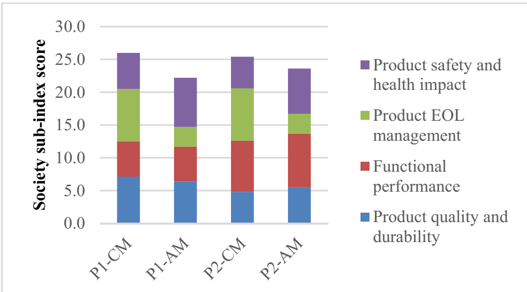

Fig. 8 Society sub-index scores for each component

6. Conclusions and future work

As identified in earlier sections, due to inherent differences in AM compared to CM, sustainability of products manufactured by each method will also be different. In this work *ProdSI* method was used to evaluate the total life cycle sustainability of products made with AM and CM. As previously mentioned, the use of an extensive evaluation method such as *ProdSI* is more suitable towards the latter part of the design stage. Hence, future work will involve developing a progressive sustainability analysis framework to support and implement design for sustainability during early design stages.

The results of the case study indicate that AM products can be more sustainable in cases where complex geometrical components are necessary. Due to the weighting and normalization procedure the scores obtained are subjective. Further, the scores are relative to components analyzed, making *ProdSI* scores obtained by one analysis incomparable with scores obtained by another.

ProdSI method's inability to take production quantity as a factor directly influencing sustainability was identified as a major drawback during this study. As discussed in earlier sections of this work, quantity of production will be a deciding factor for the manufacturer when considering AM as a manufacturing method. Since the ultimate idea of life cycle product sustainability evaluation is to provide a decision support tool enabling manufacturers to identify more sustainable options, authors suggest a breakeven-point style evaluation to integrate product sustainability and production quantity. Future work will be carried out in this regard, where an expanded new framework will be developed using modified *ProdSI* metrics (to include more direct relation to production quantity). This will be used to calculate *ProdSI* scores for different production volumes of different manufacturing methods to enable analysis of *ProdSI* score with varying production quantity to identify the 'sustainable value crossover point'.

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