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Manufacturability Assessment and Design for AM

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Abstract

The current exponential increasement of the market size and the Technology Readiness Level (TRL) of Additive Manufacturing (AM) technologies has only been met with a linear increment of additively manufactured components and final products. The causality of this inconsistency is traced to the lack of expertise knowledge, methodologies for technological assessment and design for AM that render the AM processes' competitiveness unattractive for the industrial sectors. The need to determine the added value of an AM technology for implementation to the manufacturing phases of an entity is of the essence. This work proposes an assessment method to screen the added value that an AM technology can offer to an entity by quantifying the AM utilization throughout the different product development and production stages. To quantify the AM technology assessment in terms of: final part manufacturing, flexibility to the production line, input to the engineering and design stages, cost reduction and increased performance of the final part; two already existing metrics were used (TRL and MRL), three were introduced (UPD, UFP and PPP) and the unified AM Manufacturability Assessment (AMMA) equation was created to combine the previous. The proposed method is to improve the AM industrial uptake and steer the community towards an enhanced Design for AM mentality.

Keywords: Additive Manufacturing; manufacturability; technology assessment; process evaluation; decision support; TRL; MRL

1. Introduction

The parallel advancement of Additive Manufacturing processes, machines and their complementary technologies has enabled the AM uptake for both product development and customized, low-volume production [1]. There is a demanding need to assess the added value an AM technology can bring to an entity (e.g. for an enterprise, a research and development department, or a production line) as well as in which specific phases of product development or production, AM can find application [2]. Product development comes through five distinct phases; from the product ideation and conceptual design to the manufacturing of prototypes and the transition to the production, as well as the in-between stages, where the product is engineered and its features are morphed [3][4]. AM comes into scope as a competitive family of advanced manufacturing technologies able to reduce the overall manufacturing costs and increase both the part's performance during production and life cycle [5][6]. For the manufacturing phases of the product development, AM technologies can produce parts to be used either for the final prototyping components or to assist their manufacturing (e.g. secondary structures and tooling), as shown in Fig. 1.

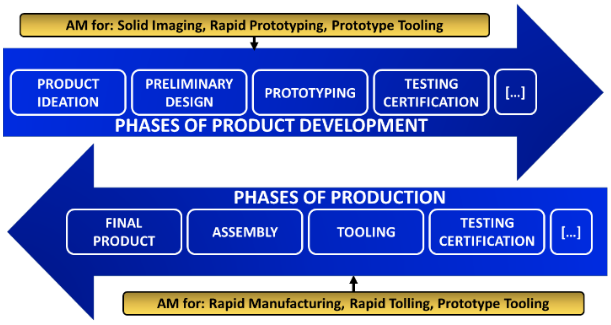

Fig. 1 Workflow of the design phases for product development

That is, AM value can be estimated for two different scenarios. The first one is as an assisting manufacturing method used during product development and production. That means that the parts that are being additively manufactured are used to assist the other manufacturing processes, and the parts that are additively manufactured do not appear at the final assembly

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itself [7]. The second case is when an AM machine produces parts that perform a functional role for the product; being part of an early stage prototype or even part of the final product [8]. Following is the proposed framework to assess the added value of an AM technology for an entity that examines the possibility of utilizing an AM process.

2. Method: Manufacturability Assessment framework of an AM technology

AM technologies are currently being implemented by major industries to manufacture very specific components [9]. Numerous case studies prove the advantageous concept of AM technologies versus conventional manufacturing, and many of them have reached final production [10]. That is, their specialized nature makes is difficult to decide on a precise assessment of the overall value of AM for the entity. The existing evaluation methodologies assess the AM technologies with a series of self-evaluated questions and checklists that assist the decision of the AM process selection [11][12].

To determine the manufacturing ability of a candidate technology that will be implemented to a specific entity and use case, the metrics of the Technology Readiness Level (TRL) [13] and Manufacturing Readiness Level (MRL) [14] are currently being used. The technological maturity (TRL) of a manufacturing process is mainly addressed to the AM process itself and the effectiveness in terms of its' performance. For the manufacturing maturity (MRL) the part design itself affects the assessment outcome. Challenging geometrical features and design aspects that have low manufacturability are negatively affecting the performance and therefore MRL. This overall assessment process is highly complex due to the abstract state of the product at the early design and development phases [12].

The proposed evaluation framework has its foundations on the TRL and MRL methods; however in order to determine the comparative value proposition of AM and the exact implementation areas for part manufacturing, three additional performance indicators are being introduced (Table 1).

The first proposed indicator is the Usage to Product Development (UPD). UPD screens the utilization of the candidate AM technology for the product development phases. It shows the percentage of the manufacturing activities that are performed with an AM machine, compared to the other manufacturing techniques during the overall product development.

Table 1 Indicators to access the AM's value to an industry

KPI	Term	Definition
TRL	Technology Readiness Level	Maturity and readiness of infusion of an emerging technology [13]
MRL	Manufacturing Readiness Level	Maturity and readiness of infusion of a process for manufacturing [14]
UPD	AM technology **U**sage to **P**roduct **D**evelopment	The usage of AM technologies at the phases of product development to assist the overall process.
UFP	**U**sage to the **F**inal **P**roduction	The usage of AM technologies at the phases of the actual production with complementary uses.
PPP	**P**ercentage of AM **P**arts to the final **P**roduct	The percentage of parts that are additively manufactured for the final product
PD	**P**roduct **D**evelopment	Are all the phases of design engineering that precede the final production

The need for prototype manufacturing that is required during the product development stages [15] can be matched by the low-batch and highly flexible production the AM has to offer. There are phases of the product development where AM technologies are superior in terms of cost efficiency and effectiveness compared to conventional manufacturing [16]. Additionally, the early AM mockups and prototypes reduce the design iterations, secure fitment and the assembly overview providing an improved engineering of the product. In more advanced applications, AM parts with functional performance that can meet the mechanical properties and material requirements can be further used for testing and validation purposes before the final mass production of the parts is initiated. All these functions within an entity that require a physical manufacturing, likewise Fig. 2, compose the overall manufacturing needs and the denominator of the indicator for the UPD is shown in Eq.(1).

$$UPD_{Numerical} = \frac{\sum No._{AM\_Technologies\_used\_for\_Product\_Dev.}}{No._{Manufacturing\_Technologies\_for\_the\_overal\_Product\_Dev.}} \quad (1)$$

Where for the UPD indicator the nominator is the manufacturing realized with AM to the overall manufacturing for the product development stages. The quantified metrical units for the calculation of the UPD, UFP, PPP, and AMMA indicators are not set and are to be determined for each specific evaluation case e.g. technical, economic or environmental based on the user's/entity's specific needs as the different point of view of each study imposes to assess different aspects of the AM process [17]. For this work numerical and volumetric metrics were selected to calculate the indicators under the scope of costs minimization.

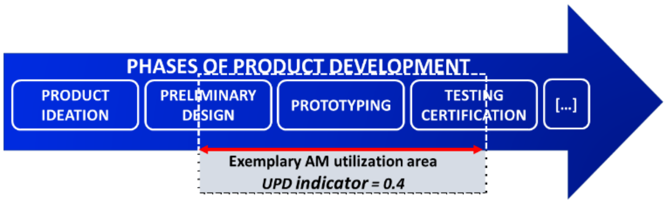

Fig. 2 Exemplary AM technology´s implementation for the five productive stages.

The Usage to the Final Production indicator (UFP) is defined in a similar manner to UPD, differentiating in the fact that it indicates the AM technologies use solely for the production phases of the final functional product as shown to Eq.(2). As such, UFP refers solely to additively manufactured components that are met in the end product.

$$UFP_{Numerical} = \frac{\sum No._{AM\_Technologies\_used\_for\_Production}}{No._{Manufacturing\_Technologies\_for\_the\_overal\_Production}} \quad (2)$$

The third indicator, Percentage of AM Parts to the final Product (PPP), describes the AM parts that are meant for end use and are not parts that will later be manufactured with another process for the same purpose. For the scenario where the entity investigates an AM technology exclusively for product development, the PPP indicator is calculated for the components that must be manufactured for these product development stages and needs. Although the manufacturing outcomes of product development stages never see it to the market, AM parts production still exists and can be screened with the PPP indicator as shown in Eq. (3) and illustrated in Fig. 3.

$$PPP_{Volumetric} = \frac{\sum V_{AM\_Parts}}{V_{Net\_Assembly}} \quad (3)$$

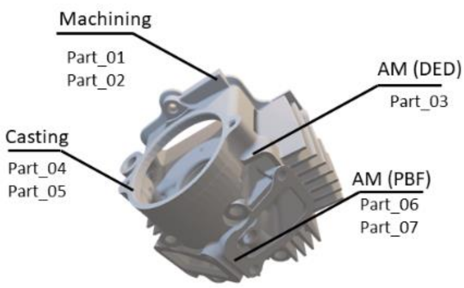

Fig. 3 Exemplary product assembly with parts from multiple manufacturing techniques

PPP can be also seen as an indirect indicator of the dual-purpose use of the AM technologies. The use of an AM machine can start at the early product development stages and then perform additionally manufacturing purposes for the final production.

At this stage, it is important to clarify the term AM manufacturability. AM Manufacturability is not a duality nature term of can-or-cannot be manufactured. By general definition manufacturability is used to describe the ease to implement a manufacturing technology to realize a part design [18]. The use and implementation of the manufacturability term varies across different AM technologies, due to their different build mechanisms, yet the same objective of reducing manufacturing costs and optimizing the overall process remains [19]. That is, AM manufacturability is to describe the part's design state and required effort to be additively manufactured (see Table 2).

Table 2 Terms definitions

Term	Definition
Manufacturability	A design part's ease to be manufactured and its capacity for cost reduction [19][20].
AM Manufacturability	A part's manufacturability when it is to be produced with an AM technique and the degree of which it utilizes the advantageous aspects of the AM technology.

To be able to univocally assess the **AM MA**nufacturability of a product for an entity, the unified metric (AMMA) is proposed Eq.(4). This metric takes into account all aforementioned indicators (TRL, MRL, UPD, UFP, and PPP) and combines them, comprising an intuitive way of comparing different applicability scenarios.

$$AMMA = a \times \left(1 - \frac{9}{TRL}\right) + b \times \left(1 - \frac{10}{MRL}\right) + c \times UPD + d \times UFP + PPP \quad (4)$$

where a, b, c, d are determined by the nature of the end user/entity and the weight factor on product development versus mass production as shown in Eq.(5)-(8).

$$a = \frac{AM\_Expertise}{Overal\_Activities} \quad (5)$$

$$b = \frac{Production\_Expertise}{Overal\_Activities} \quad (6)$$

$$c = \frac{Product\_Development\_Activities}{Overal\_Activities} \quad (7)$$

$$d = \frac{Mass / Custom\_Manufacturing\_Activities}{Overal\_Activities} \quad (8)$$

3. AMMA indicator as part of the AM Design

A detailed elaboration of the individual variables and constants of the AMMA indicator follows. Its relevance with the DfAM rules and part design is to be exploited for improved part production and performance during the part life cycle. The AMMA indicator assesses the AM technology's value by considering:

1. The entity's manufacturing nature
2. The entity's expertise in AM
3. The AM's technological maturity
4. The AM's manufacturing performance for the part production

The *a* and *b* constants of Eq. (4) reflect the entity's expertise on AM and therefore indicating its capacity to dedicate resources to increase the AM technology's TLR for their specific technological needs and the equivalent incensement of MRL for the combination of an AM technology with a specific product. The TRL of the AM technology is strictly related to the AM process, equipment and complementary technologies. The MRL is a combination of the technology's capabilities alongside the product's manufacturability. Due to the buildability constrains of each AM technology certain geometrical features of the part can affect the efficiency of the production. That is, from the Eq. (4) *a* parameter indicates the user's capacity to allocate expertise to increase the TRL of the AM technology and process, where *b* indicated the user's capacity to allocate expertise to increase the MRL for the combination of the AM technology with a product.

The *c* and *d* constants indicate the entity's future activities and goals in terms of product development and production accordingly. For instance, if an entity has high UPD for its product development activities but aims to swift the nature of its manufacturing towards final production the c factor will compensate for that by reducing the effect of UPD for the total AMMA portion.

The overall AMMA assessment indicator is affected by the part design. This is because the individual quantities of MRL and PPP are directly connected. The MRL indicator is calculated from the manufacturing maturity of the AM technology that will produce the part. That is, the part to be manufactured effects the overall manufacturing process effectiveness and efficiency. The PPP increases as the design mentality shift towards the freeform Additive Manufacturing nature.

The MRL indicator for an AM technology results from both adequacy of the product design and the TRL of the AM technology. The PPP results from the adopted design mentality. More AM parts are met at final products as the design mentality shifts towards DfAM and complex geometries for optimized performance are designed. The status of what the MRL and the PPP screen, can be improved with the backpropagation of DfAM information to the design phases. The enhanced design engineer's competences and expert knowledge of the AM process mechanisms is causing a shift in the design mindset; which in combination with the uptake of the generative design algorithms, lead the overall design process away from the feature base mentality towards a function driven approach. This results in more frequent AM designs that extend the AM's implementation for series manufacturing and final production.

The AM design competences create a realistic awareness of the AM capabilities and how to better implement the true AM value to the designs; and at the same time have the decision-making ability to decide when to produce components with conventional manufacturing.

Thus, appropriate AM design methods at the early stages of the product development, that take into account AM manufacturability restrictions have the potential to increase AMMA, making AM an attractive manufacturing method for industrial applications; either at the product development stage or in actual final production.

4. Conclusion and Future Work: Implementing the Manufacturability Assessment framework

The evaluation of an AM technology is the initial step of the extensive AM design methodology for the complete engineering of a part and its production. The next step is the evaluation of the part's design manufacturability with the candidate AM process. These two steps feed each other with information required to optimize the AM production's performance (Fig. 4).

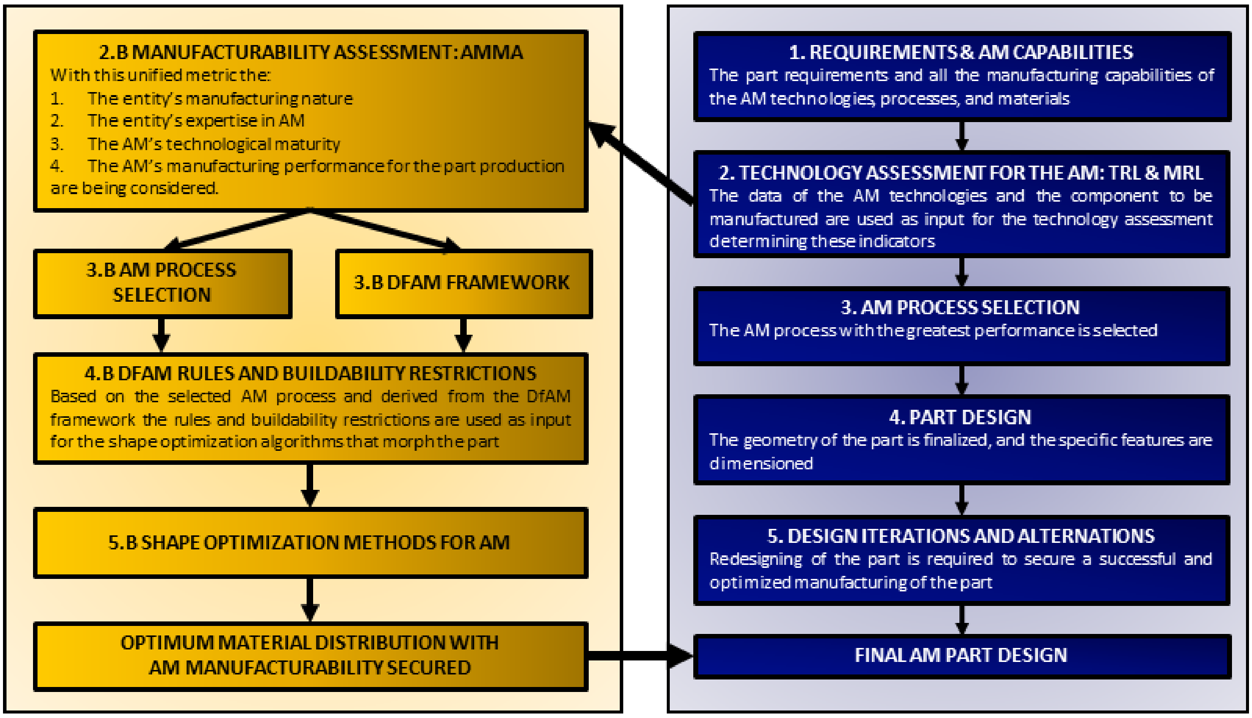

Fig. 4 AM Design Expert System for an enhanced part design approach utilizing the manufacturability assessment.

The overall design process calls for multiple data inputs at all of its stages. This information is used to converge from all the designing options and decide upon the geometric design features that abide to the manufacturability restrictions. As the engineering design progresses, more details regarding the geometric features, material and dimensional properties are defined. That is, an early estimation of the AM technology's usefulness is to be of low accuracy. For the technology assessment to get the greatest possible AM verdict, it is crucial to address the AM manufacturability concerns of the technology at the early design stages. The proposed methodology is to be implemented from an entity that has manufacturing activities e.g. a part manufacturer or an R&D department.

New designing approaches with algorithmic complex-shape optimization methods can significantly contribute towards increasing the industrial use of the AM technologies. The crucial key-point is the manufacturability aspect of AM, imposing constraints when morphing the geometry of the part.

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