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The role of Design for Additive Manufacturing in the successful economical introduction of AM

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Abstract

Additive manufacturing (AM) has been around for decades while it has been at the focus point of attention for home users and industry for only a few years. The reasons for this recent awareness can be attributed to the simplicity of the process, which allows it to be used to make almost any shape in any material. This is one of the reasons companies investigate the possibilities of AM as a strategic advantage in their line of business.. In this paper studies are presented in which the introduction of AM technologies within industry is the main focus. Design for AM methodologies are presented and linked to commercial successful introduction of AM in industry. It is shown that for this introduction the role of product (re)design for AM is of major importance to successfully apply AM as a production methodology. A new (re) design strategy for AM based product development is presented, from a product life cycle viewpoint (section 2) and a product level (section 4.1)

Keywords: DfAM; Additive Manufacturing; Design optimization, Cost

1. Introduction

Additive manufacturing is not a process but the container phrase for a whole group of processes. These processes share some common advantages, but also all have their own characteristics. This papers focusses on what steps companies have to take to inform themselves on the possible applicability of AM (section 2). Furthermore, some considerations are presented that are used to evaluated suitability of AM (section 3). In section 4 it is shown why and how redesign of parts is essential to increase the change of economically successful introduction of the technology. Finally, a sequence of design steps is proposed, tailored to the assessments of material and process suitability late in the product (re)design process.

2. A novel DfAM strategy based on the AM product life cycle

To assess the use of AM it is important to consider the implication of AM in all life cycle aspects of the product development cycle. In both scientific, popular and commercial literature a lot of unstructured knowledge and information is available on the pros and cons of AM. In order to structure the available data Goutier [1] presented a modified product development cycle of Pahl and Beitz [2], linking product development steps to both information gathering and Am implementation steps (See fig. 1). The steps presented in this model are addressed and explained in sections 2.1-2.8.

2.1. Market need and AM potential.

For each scenario it is important to clearly state the market need and link it to the potential benefits of AM. In [3], [4] & [5] the following generic benefits of AM are listed.

- Best cost effective solution
- Easy product customization
- Reduced time to market
- Increased flexibility in product development

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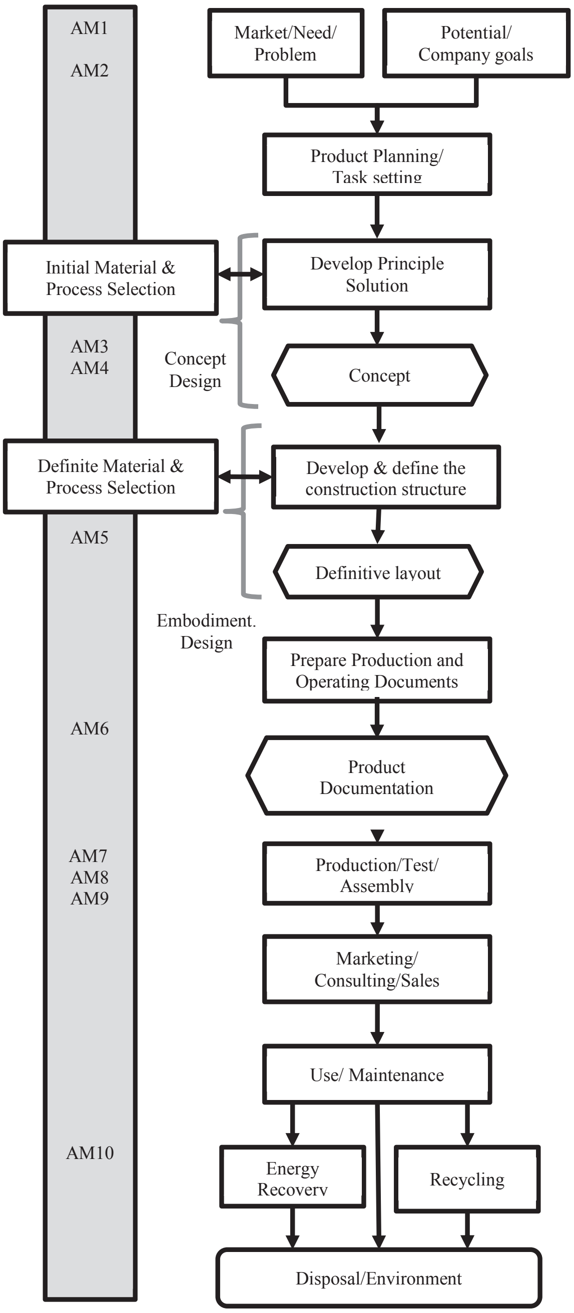

Figure 1. AM related life cycle consideration related to the Product development model from Pahl & Beitz [2]. AM1 – AM10 respectively address: 1Inform and inspire on AM potential. 2 Asses AM suitability. 3 Design for AM. 4 Material and process screening. 5 Material and process ranking. 6 CAD and production preparation. 7 Cost estimation. 8 Post processing. 9 Effects of the use of AM on testing. 10 Environmental impact of AM. Picture based on the work of [1]

- Distributed manufacturing
- Supply chain simplification
- Complexity for free
- Functional integration
- Part consolidation
- Functionally graded materials
- Efficient use of materials

Next to these possible advantages there are some generic technical and organizational challenges related to AM that still need to be overcome by the AM community [5].

- Standards and certification is lacking
- Intellectual property of digital models & designs is not clearly defined
- Complexity of the process control is high.
- Quality control during processing is lacking.
- The limited availability of AM materials
- Characterization of mechanical and thermal properties is not at the same standard is found in more classical production processes
- High cost of AM machines and materials
- Software capabilities are not sufficient to reach full AM capabilities of models.
- High surface roughness in AM produced products.
- The use and removal of support structures.

Without a thorough understanding of these pros and cons a reliable evaluation of the envisioned market need is troublesome.

2.2. Design for Additive Manufacturing

Companies investigation the potential of AM generally do so based on a new business model or to investigate what role AM can play within their current business model. Especially in the latter case the obtainable economic benefits (in any of the life cycle stages) can be disappointing if the design has not been designed or optimized for AM. If products are already designed for another process, for example cnc milling, chances are that this is also the most economical process to produce that part. As stated in [4] DfAM should "*maximize product performance through the synthesis of shapes, sizes, hierarchical structures and material compositions, subject to the capabilities of AM technologies*". To ensure that product performance is maximized several DfAM strategies have been developed (see section 4).

2.3. Software and model generation

Traditionally the models for part development are created using CAD tools for which the design features have been optimized for subtractive production methods like turning and milling. They are translated to STL and AMF file (AMF has native support for color, materials, lattices, and constellations) formats for AM purposes. Next to the traditional product modeling workflow the 3D models are also produced using topology optimization (for example fig. 3), advanced AM focused design tools (see also section 4) and scanning hardware.

2.4. Material selection for AM

When selecting the material for an AM based product there are a few points that need attention. First of all, the number of materials available for AM is limited compared to those available for other processes; for example Senvol [7] produces an overview of commercially available materials for mainstream AM processes and contains just a fraction of the number of materials available for other production processes.

Of these materials not all data (for example fatigue strength) is available, or the data has to be harvested from scientific publications. Furthermore, the resulting material propertied are depending on the production settings and product orientation during the build.

Finally, the listed and measured material properties sometimes show great discrepancies; for example [8] showed differences between the claimed and measured values of strain at break (50%) and Young's modulus (78%).

Goutier [1] proposes to use screening and ranking steps, as also proposed by Ashby [9], for both material and process selection. In the screening step all materials/processes are selected that are applicable. In the ranking step the suitable candidates are ranking based on an optimization criterion.

2.5. Process selection for AM

Next to material compatibility and building volume Kim [11] has defined the following list of part properties that directly relate to the buildable geometry for certain processes: Support structures, surface quality, curling/warping, minimal feature sizes, shape accuracy, resolution and anisotropy. For example, in [10] and [11] geometry as build and as designed were compared and discrepancies up to 0.2 mm were found. In measurements related to anisotropy, variations in measured mechanical values were found for SLS of 24%, FDM 42% and SL of 20% [11][12]. Finally, the designer should understand that the process parameters themselves (for example layer thickness, power and scan speed settings, hatch spacing) can have significant influence on the outcome of the geometry and material properties of the printed product.

2.6. AM post processing

Knowledge and understanding of the post processing steps, needed to enhance part properties or to reduce effects of the AM process, is an important but often overseen step in the product development process. According to Gibson [4] the most commonly used steps are Support material removal, Surface texture improvements, accuracy & aesthetics improvements, property enhancement using (non) thermal techniques and preparation as use as a pattern. Post processing steps can be costly, labor intensive and/or time consuming and might require pre-production redesign of the product.

2.7. Time and Cost implications

In Thomson [13] an overview can be found on several cost models for AM, both generic and process specific. It is shown there that that the Machine costs material costs are the major contributors to the relative high cost of parts produced using AM processes. As the AM process itself is (still) a relatively slow process, the production time and with that the relative contribution of machine cost to the total product price, is high. Also the price of stock materials used in AM processes is relatively high. [14] reports on raw material prices as high as 1100 €/kg, being a factor 50-100 times more expensive than the non-AM versions of the same material.

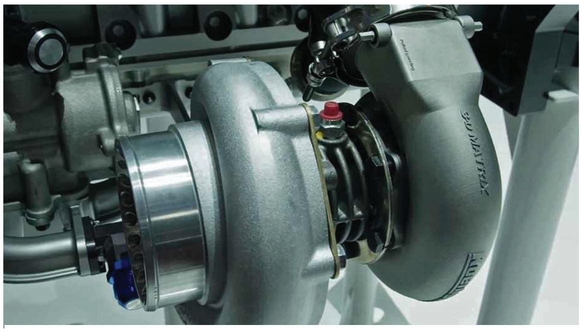

Figure 2. The 3D printed variable turbo from Koningsegg. [6]

2.8. Environmental impact of AM.

Most research on AM and the environmental impact focusses on the energy usage during production [15], [16], [17], [18]. Especially for powder bed processes this energy consumption was determined to be significant. When similar parts are produced using injection molding and laser based AM processes, [19] reports that laser based processes may consume 50-100 times the amount of electrical energy than injection molding. Reduction of energy consumption for powder bed processes can partly be achieved by the designer and/or machine operator by orienting the part so minimal build height is needed. Also some machines can reduce energy consumption by using adaptable process chamber sizes. Finally, new studies show that in LS, FDM and powder bed processes fumes and small particles are released that can be a possible health issue [20], [21]. The long term effects of these emissions are still largely unknown.

3. Assessing AM Suitability

According to [22], determining if AM is suitable for a part/market can be determined by answering 3 questions:

- Does implementing AM offer business opportunities that will give the company a potential competitive advantage?
- Is the use of AM technologically feasible?
- Is the use of AM economically feasible?

The points related to the first question are discussed in section 2.1. The points related to the second question are related to the material (section 2.4) and process chain (sections 2.5 and 2.6) compatibility. Finally, economic feasibility is related to part cost, life cycle costs and economic benefits after the production phase. Based on Doubrovski [22] a subdivision of AM based application areas can be defined.

1. Prototyping.

2. **New** products and business models specifically focused on benefits stemming from AM (see par 2.1)
3. AM produced parts and assemblies that are going to be used within **existing** products. Here a subdivision can be made between (a) redesign of so economic benefits after AM based production can be obtained and (b) AM used to reproduce parts with the focus on economic benefits during production.

For prototyping purposes AM has long been known to play an important role; this item does not need further discussion. To evaluate the economics feasibility of new products and business models the discriminatory aspects of section 2 have to be evaluated against the new business model. For the products in the 3rd group the evaluation can be more focused; 3a compares the (increased) production cost to the direct benefits of the redesigned part, while the last one (3b) only compares production cost directly. Well know examples of economic benefits after production (category 3a) are the variable turbo from Koningsegg [6] (fig. 2) and the fuel nozzle for the leap engine from GE [23]. Both among other use part consolidation to reduce wear and increase efficiency. Lindeman among other utilizes topology optimization [25] (fig 3) with the goal of weight reduction for airplanes.

Especially point 3b is a reason for many companies to investigate the use of AM while the window of opportunity for economic benefits here is small. Based on the information from the previous section this argument can be supported. In order evaluate if this window exists the following aspects could be inspected:

- The original design should be produced (unaltered) in low numbers (up to 1000 parts).
- The original design should be of limited overall size as many machines use a set build volume.
- Should be complex and labor intensive to produce, as these factors might be an indication that the original product is expensive to produce.
- Furthermore, to ensure that the labor extensive post processing steps are minimized, it should not be critical regarding low surface quality (typically R_a 15 and higher) and low accuracy (up to 0.2 mm).
- Finally, as material characteristics from the material/process combination used in AM will differ from material characteristics from the original material/process combination, the product should be insensitive to these new characteristics.

It can be concluded that commercially successful adaptations of the use of AM technology are characterized by business models tailored to AM or are based on, for AM purposes, redesigned products that mainly show their (financial) benefits it the use stage of the products. For that reason, the next section will focus on the latter topic, product (re)design strategies for AM.

4. Design for Additive Manufacturing (DfAM) strategies

This section presents an overview of existing DfAM strategies. They are based on early selection of both the AM process and material. In 4.2 an approach to DfAM is presented that postpones this choice, which allows the designers to test the generic applicability of AM instead of the applicability of a certain process or material.

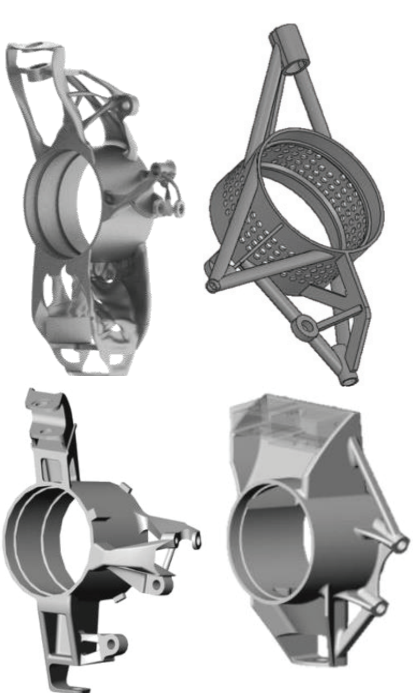

Figure 3 Examples of design strategies as propsed by Lindeman [25]. Top left: CAD remodelling of TO results. Top right: CAD modelling using design rules for AM (no TO). Bottom left: Use of TO and standard CAD features. Bottom right: Combination of TO, CAD features and design rules

4.1. Literature overview of DfAM strategies.

As stated in section 3, in most cases it is necessary to redesign products to fully exploit the benefits of AM. Design for manufacturing guidelines no longer apply and new design strategies have been developed to exploit possible benefits of AM parts and products.

Maiden [25] has created a database of design features that are only achievable in an economic way when using AM. Although it is an important source of inspiration, the database however does not link the design features to AM processes or does it define how the overall part should be designed/optimized for AM.

Rosen [3] proposes to use cellular structures in AM products as they are easy to produce with AM and are characterized by high strength/low mass ratios, show high levels of energy absorption and are good thermal and acoustic isolators. He also proposes a design strategy that links functional requirements to part properties that satisfies those requirements. Then suitable cellular structures are mapped onto these properties. In the final stage simulations are executed to verify that the as-designed part behaves as the as-produced part.

Ponche [26] distinguishes between global and partial design for AM. In partial design already a product design, based on traditional manufacturing methods, exist. When this is the case the redesign is in most cases only locally optimized for AM. In global design strategies the entire design is created especially for AM, which should lead a higher degree of optimization of the product design. Ponche defines new part designs by defining functional surfaces and volumes of that part, and empty volumes that will be occupied by other parts. A new design is found when all functional surface have been connected successfully. A drawback of this method is that is has to be applied after material and process selection, as this information is needed during the design synthesis phase. Furthermore, based on the method proposed it will not result in the use of proven alternative solutions for design for AM, like topology optimization and the use of lattice structures.

Next to the previous mentioned methods, where the designer controls to outcome of the design process directly, many design strategies exist that utilize topology optimization (TO), in most cases to reduce part weight (see for example Salonitis [28]). With topology optimization the computer determines the optimal geometry based on a sets of constraints. To do so, the solution space is subdivided in small elements. The constraints and the solution algorithm together determine what elements are part of the final product and what elements not. Based on these methods geometries emerge that have excellent weight to strength or stiffness ratio's, have excellent properties in applications that need lightweight constructions. They furthermore result in shapes of a geometric complexity level that AM production is required. This random geometry can also be a drawback. Lindeman [24], fig 3, proposed several strategies to deal with the shapes that are produced using TO.

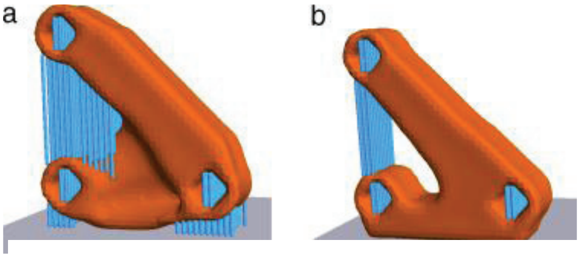

Figure 4 Example of TO optimization focussing on both weight reduction and the reduction of the use of support structures. Left: design based on TO without constraints on the support structures. Right: the updated design. Mirzendehdel[27]

Standard use of TO strategies use mechanical constraints and results in complex geometrical solutions. These solutions also may include shapes less optimal for AM production methods. In [27] a TO variant is presented where the demands of the AM process are also included in the constraint domain. It introduces a combined sensitivity that balances weight reduction and low levels of support materials needed.

4.2. DfAM to evaluate part suitability for AM.

In the previous section a short overview was presented on some of the major direction in the world of DfAM. For a more elaborate overview please see [13]. The strategies presented in the previous section try to incorporate the material and process characteristics of the AM processes in an early stage. When assessing the general suitability of a product idea for AM the moment that data of individual processes or materials influence the selection process should be positioned late in the selection process. For that reason Goutier [1] explored a design strategy was explored that postpones that moment as much as possible.

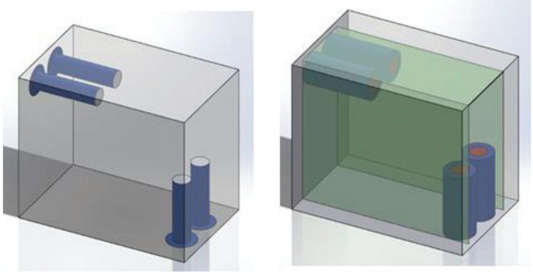

Figure 5. Left: The first stage of modelling a hypothetical bracket. For holes are defined for mounting purposes. Furthermore 4 flat surfaces around the holes have been defined for flat mounting to other surfaces. The bracket will be loaded with 500 N. Right The second stage of modelling that includes the empty volumes (red) and the minimal and maximal dimensions of the product.

The general approach of the strategy is based on the Ashby method [9]. Both screening and ranking steps are executed on candidate materials and processes late in the assessment path. The design process of a hypothetical mounting bracket (Fig 5 and 6) is used as an illustration of the proposed method.

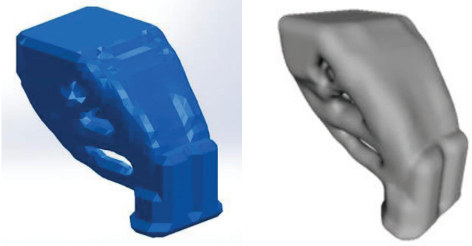

Figure 6: Left: A topology optimized version of the bracket. Right: Final design after model refinement.

In the first step the functional requirements for the part are defined.

- Function; What does the component do?
- Constraints; What non-negotiable conditions must be met?
- Objective ; What is to be maximized or minimized?
- Free variables; What parameters of the problem is the designer free to change?

In line with the work of Ponche [26] functional and empty volumes are defined (fig 5, left). These are derived from various factors such as the need for the volume to resist punctures or for it to be thick enough for threads to be added in a post processing step. Similarly, the required empty volumes can be identified; these are volumes that are required to be empty for other parts to be inserted or volumes required for connectors (e.g. bolts, screws) in the assembly Both the functional and the empty volumes are part of the constraints domain of the design.

Next, the minimum and maximum part dimensions will need to be established (fig 5, right). The minimum part dimensions are the smallest dimensions required to contain all the functional volumes. The maximum dimensions follow from the intended use of the part, for example the required fit of the part into a larger assembly, or requirements related to the mobility of the product.

Based on this first exploration of the design space a first geometrical model of the part has to be developed. That can for example be done using the volume connecting method of [26] or by using a TO strategy [24].

The identified constraints from the first step can now be used for screening of suitable materials and processes. For the process screening the minimum and maximum part dimensions can be used to optimize for variations in the dimensions of the processing platform of the AM technique.

For the bracket in the example, Finite Element Analysis showed that none of the available plastics would be capable of achieving the constraint on deflection, even if the maximum volume was completely filled with material. As such plastics can be eliminated in the screening phase, as well as AM processes that are compatible with plastics only.

5. Conclusion

A set of characteristics is proposed that define the product window in producing parts with AM without redesign still might be commercially interesting. For all other product variants this paper proposed a novel product redesign strategy. Future work will focus on (computer support) of methods for early establishment of suitability of parts for AM. This work should also establish the practical suitability of the method.

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