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Procedia CIRP 84 (2019) 688–693

www.elsevier.com/locate/procedia

29th CIRP Design 2019 (CIRP Design 2019)

Development of an integrated design methodology model for quality and throughput of Additive Manufacturing processes

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Abstract

Additive manufacturing (AM) has risen to be a substantial part of modern manufacturing due to its unique capabilities and has already been fondly adopted in various fields especially in the aerospace. In order to fully harness the benefits of this revolutionary manufacturing technology, this article aims to develop a practical integrated design methodology that can be used to enhance quality and throughput of AM processes. In doing so, investigation were conducted to examine an AM aero-based component through design tools that allow designers to consider an integrated process chain, from component design to pre-processing, manufacturing (laser bed fusion building), post-processing and finished part. The developed design model integrated with decision tools will assist the design experts in developing new knowledge that looks beyond the familiar Design for Additive Manufacturing (DfAM) rather to Design towards product Certification (DoC). In addition, this will serve as an effective design guidance that can inform proper design planning and optimization in aerospace industry production.

Keywords: Additive Manufacturing; Design; Production

1. Introduction

Design is generally known to influence the structure of production at all levels in a beneficial way, while standard production system positively affects inextricable environmental and sustainability concerns, considerations and initiatives [1]. New production design techniques could help overcome stagnant productivity especially in manufacturing thus paving way for more value-added activity. The new technologies of the Fourth Industrial Revolution such as the Additive Manufacturing (AM) process have the potential to transform the global structure of production. Hence, it is necessary to deploy these emerging technologies in ways that addresses and adapts to perfect production scheme.

Additive manufacturing (AM) has been defined as the process of joining or stacking materials to produce objects from 3D modelling usually layer upon layer as against subtractive manufacturing technologies, which involves traditional machining [1-3]. The many benefits AM offers are becoming increasingly useful in engineering design and the goal of a design is to either consolidate parts into one or decompose and recombine parts into new ones through translation of conceptual design phase to product development phase within a short manufacturing cycle time. Hence, significant improvement in the degree of freedom of design, are the initiating factors drawing researchers' attention in the emerging field of additive manufacturing [4]. However, there is a need for a good process design that can integrate product and technical requirements, as well as the manufacturing process in order to enhance product's quality and high throughput using AM. This is possible through product design and simultaneous manufacturing via effective integration of technical and product requirements as well as process parameters. Likewise, reduction in production costs, time for product development, and tolerance deficiencies is

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Peer-review under responsibility of the scientific committee of the CIRP Design Conference 2019.
10.1016/j.procir.2019.04.177

obtainable in this regard [5-7]. Furthermore, the design process model allows incorporation of all relevant specifications and production factors that helps in making important decisions such as the selection of materials and manufacturing processes [8-10]. The manufacturer's experience may neither be sufficient nor reliable for good decision making with respect to the market dynamics and emerging technologies, hence it is of utmost priority to develop the right framework for process design. A good AM process design seeks to reduce the manufacturing cycle time, increase productivity and profitability, enhance the quality and performance of the finished products and increase the conversion rate of raw materials to finished products thereby decreasing wastages [11]. The process of AM needs consideration for the design requirements alongside the associated constraints in part manufacturing. Over the years, efforts have been made to solve the challenges of material and process selection through an interdisciplinary approach. The Multiple Objective Optimization (MOO) comprising of the Generic Algorithm (GA), Multiple Objective Generic Algorithm (MOGA), neural network etc. and the Multi-criteria Decision Making (MCDM) comprising of ranking the feasible solutions among alternatives, screening, Multi-Attribute Decision Making (MADM), knowledge based systems, material selection process, Analytical Hierarchy Process (AHP), case based reasoning, fuzzy DM, fuzzy-AHP etc. have been deployed in a bid to obtain the best process and the most feasible solution. Many researchers who have worked on the development of integrated process design for AM considering the criteria of functional requirements, cost data, environmental impact, material classification and manufacturing processes [12-15]. However, the research target is to increase the understanding of the phenomena of design in all its complexity and the development and validation of knowledge-based systems (KBS) methods and tools to improve the observed situations through effective design [17]. The field of literature commonly regarded as a design methodology is primarily concerned with the study of how designers work and think as well as the establishment of appropriate structures for the design process. It also involves the development and application of new design methods, techniques, or procedures as well as its reflection on the nature and extent of design knowledge geared towards design problems application [18].

The methods often used in the study of design varies, starting with reports from the designers themselves, to observation of designers at work, experimental studies based on protocol analysis and interviews with professional designers. However, there is no single model, which is agreed to specifically provide a satisfactory description of the design process. Instead, most methods have a well-defined and narrow focus ranging from the generation of mechanism concepts to implementation [19]. However, the implementation and use of such methods always pose some challenges [20]. To fully exploit the freedom of design and customization, engineers will have to create products that operate within systems, with a growing information-systems component such as AM processes. Progressively, more product value will be derived from a product's digital component rather than its physical components.

Table 1. Category of Design Methods adapted from [23]

This work discusses the proposed methodology focusing on structuring the integrated design process knowledge with ideal decision-making tool in each of the design stages; with efforts to validate the throughput and quality part of additive manufacturing process of the framework using an illustration.

2. Methodology

Technologies are known to allow producers to design and manufacture with speed and good performance. Product development has traditionally followed a sequential process, from Research and Development (R&D), product concept and design, along with product engineering and supply chain management, to marketing and aftermarket services. The key factors to be considered for the development of the integrated process design holistically are: product and production requirements, material selection, selection of appropriate AM technique, the manufacturability cycle time, the dimensional tolerances and finish requirements, need for post processing or otherwise (See Fig. 1).

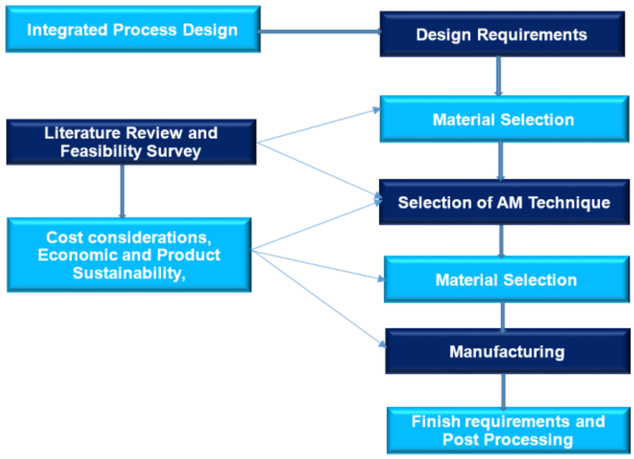

Fig. 1. Framework for the development of integrated design process

2.1 Design methods

Design methods are regarded as any procedures, techniques, aids or tools for designing [21]. Different design methods have different purposes and may be relevant and applicable to different aspects or stages of the design process. Some design methods have been criticised as being over-formalised thereby posing a hindrance to creativity. Today, the design process for AM often starts with an existing design, especially since the goal is to make it a current production process. However, due to the complexity and nature of AM processes that involves making important decisions in the manufacturing processes, the use of proper design methods would help towards a structured approach to reduce errors [22]. Design methods have been further characterized into three broad categories: design for the generation of ideas for concept design, design for concept design evaluation and design for a specific design purpose [23], which aims to aid designers in improving their design as in (Table 1).

Design Methods	Examples	Purpose
Generation of ideas for concept design	Brainstorming, Fish bone diagram	To provide ideas or inspiration
Concept design evaluation	Pugh's Matrix, Morphological Chart, Checklist, Weighting and Rating, Combined Method	Detailing mental blocks for creativity and widening the search space
Specific design purposes	Design for Assembly, Design for Manufacture, Quality Function Deployment, Failure Modes and Effect Analysis, Taguchi Methods, Functional Analysis Method, Function-Cost-Method, Design for Cost, Value Engineering, Activity Based Costing	To avoid error and improve decision process in product development process

A number of formal structures and frameworks aimed at a better understanding of the design process have been suggested for different disciplines such as engineering design [24] and industrial design [25]. Depending on the domain and on the problem being addressed, design methodologies are fixed but varies. The popular classification of design is into three broad methodologies: analytical, procedural, and experimental design [23]. The concepts behind this classification are those of object, attributes, and operations as well as the different roles that are assigned to humans and machines in these classes of design methods. Pahl and Beitz [24] outlined a model of the design process for mechanical design that considers not only the sequence of stages, but also what the output of each stage should be, as they consider this to be a strategic guideline for design. The division of the design process is in four phases as follows: Process planning, conceptual design, embodiment design and detail design.

2.2 Challenges facing a designer using Additive Manufacturing

Design for Additive Manufacturing (DfAM) is an emerging branch of mechanical design. Because it calls some changes in the way things must be done, along with it appears a certain degree of resistance, from the early stages of the conceptual design to its virtual embodiment [20]. The first challenge for the designer is to avoid locking on current designs or traditional practices of Design for Manufacturing and Assembly (DfMA). Another is to virtually create complex shapes, either manually, by the means of tools for freeform modelling and reverse engineering or with material distribution algorithms. This takes a certain expertise and know-how on advanced software. While considering the capabilities (and constraints) of AM, a deep understanding of AM processes and of their design implications is required in line with a design environment relevant for DfAM as follows.

i. synthesizing the shapes, sizes, geometric structures, material compositions to leverage additive processes capabilities and achieve desired product performance
ii. supporting the modelling of specifications and parts, as well as the process planning and manufacturing simulations

In the development of an integrated concept of an industrial Additive Manufacturing processes, it is necessary to identify the principal activities that can be identified as common to the entire process concept. The DfAM knowledge that emerged from the literature was classified according to the typologies of design guidance presented in Table 2.

Table 2. Typologies of design adapted from [27]

Typology	Definition
Design principles	Design principles are high-level directions derived inductively from extensive experience and/or empirical evidence. They can provide indications on how to design efficiently and exploit AM capabilities. Therefore, suitable for supporting creative activities such as concept generation.
Design guidelines	Design guidelines are context-dependent directives that provide design process direction to increase the chance of reaching a successful solution.
Design rules	Design rules provide knowledge where the relationship between cause and effect is well known and they produce predictable and reliable results. Generally employed at the detail design stage, validity is limited to a specific material and process combination
Process guidelines	Process guidelines are the information on how to perform the AM execution and achieve the desired part requirements. This define machine parameters and post-processing operations and the awareness of process guidelines benefits the design process.
Specifications	Specifications are generally codified by international standards and communication through engineering drawings. These are information about characteristics of AM production process such as resolution (layer thickness), part orientation, infill (percentage and shape) and mechanical properties of the material (e-material) without affecting the CAD geometry.
Process selection tools	Process selection tools are decision making aids in selecting the appropriate processes. This nature can be both qualitative (for the early stages of the design process) and quantitative (for the later stages where more detailed information about the part is available).

2.3 Generative Design of Additive Manufacturing

Today, a few CAD producers present their software as seamless design environments for additive manufacturing while others push prototypes of generative design platforms to the market. Generative design brings the promises of interactive environments for parametric shape rule definition and design exploration in a guided movement through a space of possibilities [16]. Generative design is a powerful concept that automates different types of optimization - topology, lattice-based structures, and strut/beam structures [25]. Relying on the infinite computing power of the cloud, it generates design alternatives to meet the exact specifications, based on a set of input parameters (desired weight requirements, maximum stress/strain) defined by a designer. This nascent approach and technology is a shift in the paradigm of designing things and a promising concept to improve the overall design quality, efficiency and performance. It is aimed at assisting engineers in the additive manufacturing of lightweight and load-bearing components for the aerospace, automotive, medical implant industries and industrial equipment [24]. However, as CAD solutions get smarter, even a generative design algorithm still requires skillful engineers to determine the relevant specifications as inputs within accurate decisions.

3. Implementation of the Design for Additive Manufacturing (DfAM) Technique

Since AM is no longer just a quick way of making models, but rather a manufacturing approach that can be used either directly or indirectly to produce finished parts. Hence, the most effective way to achieve this is to give designers a methodological approach for designing for AM. Most design aid tools available currently support design at the preliminary stage, such as quality function deployment, or at a later stage of design, such as detail design, with various CAD tools [25]. Strategic approaches that support early stages of design for conventional manufacturing such as design for manufacture and assembly (DFM and DFA) are also available and useful. However, some unresolved issues exist within the DfAM paradigm, restricting its applicability. The need to integrate decision supporting design aid tool for the AM parts or product implementation is imminent.

A primary finding is the development of strategies necessary to meet future design challenges for AM is the identification of the "Integrated Product and Process Development (IPPD) method". The IPPD as defined is a management methodology (or strategy) that incorporates a systematic approach to the early integration and concurrent application of all the disciplines that play a part throughout a system's design life cycle."[28].

3.1 Decision Support Structures for Design

The IPPD is a technique that integrates all acquisition activities starting with requirements definition through production, fielding/deployment and operational support in order to optimize the design, manufacturing, and supportability processes [25]. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements [25].

Most design tasks and activities involve decision making concerning issues such as function, structure, configuration, material and geometry of the designed product [27]. Decision support is an essential element that can support a trade-off process and can be used to focus efforts on design goals [25]. Therefore, an integrated model is proposed to guide the development of product within the IPPD framework of Concurrent Engineering principles. To implement the IPPD strategy, the core approach developed in this study is a top-down decision support design process (See Fig 2).

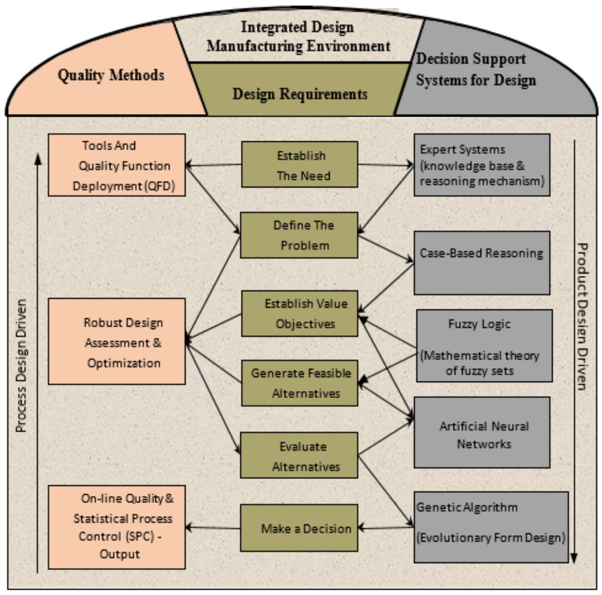

Fig. 2. Integrated design model with decision support tools in determining quality and production throughput.

3.2 Integrated model consideration and approach formalization

AM has been commonly used to produce prototypes and finished parts directly from CAD models and has been used extensively in the embodiment design stage to check form, fit and function [13]. Industrial designers use prototypes to access a product concept, whereas engineering designers use prototypes to test and analyze the technical and functional aspects of a final design. The informed designer can make use of these model interrelationships and the strengths of AM processes during the design stage. A plethora of additive processes is available based on several technologies, as categorized in different groups according to the ASTM International standard [26]. Each category uses a special kind of technology for production. The standard entitled 'Standard Practice – Guide for Design for Additive Manufacturing' (ISO/ASTM) focuses on the technical elements of a component as a basis for process selection, such as material, surface and geometrical considerations; and static and dynamic physical properties [26].

To establish design and ensure manufacturability of features, preventing material problems, and addressing other manufacturing concerns. Therefore, an interesting practical example is considered for a highly rated, complex product towards design for certification requirements. Produced by an AM technology known as Selective Laser Manufacturing (SLM). The proposed approach start with "establishing the need" and conclude with "make a decision". The visual knowledge is displayed for an aero-structural component, namely; impeller (See Fig 3).

Design fundamentals can be deduced from the design guidelines:

Features; **Geometry related parameters;** *Material Parameters;* ***Machine parameters***

Design Principle: $DP_{Feature}$

= **f (Geometry related parameters (G),**

Material Parameters (M), ***Machine parameters (P))***

$DP_{Feature} = f(\mathbf{d_1, d_2 \ldots d_x}, m_1, m_2 \ldots m_x, \mathbf{r_1, r_2 \ldots r_x})$

Where $\mathbf{d_1}$ **to** $\mathbf{d_x}$, m_1 to m_x, $\mathbf{r_1}$ **to** $\mathbf{r_x}$ represent feature specific parameters.

Considering the case within Laser Power Bed Fusion (PBF) process, the versatile AM strategies with intricate features.

Where t is the wall thickness, β is the orientation, h is the height, z is the powder size, f is the flowability of the powder, **P** is the laser power, **S** is the scan speed, t is the layer thickness. This basic for the development of production procedures.

Specific values may sometimes depend on process, machine manufacturer, or user, but the basic premise supports the tailoring of customized rules. The highest level of abstraction; is synergizing the design guidelines, principles and rules applying across categories of processes.

Design Guideline $DG = [dg_1, dg_2, dg_3 \ldots dg_n]$

Design Fundamental $DF = [df_1, df_2, df_3 \ldots df_n]$

Design Principle $DP = [dp_1, dp_2, dp_3 \ldots dp_n]$

Design Rule $DR = [dr_1, dr_2, dr_3 \ldots dr_n]$

Provided with this solid guide-to-principle-to-rule approach (GPR) design foundation, application specific can be derived as new data and information becomes available within a computer-integrated environment. In order to reduce design cycle time, the rule based GPR approach is used for factors such as shapes, sizes, material compositions and hierarchical structures as listed per stage in Fig 3, for a seamless integration in the additive manufacturing production systems.

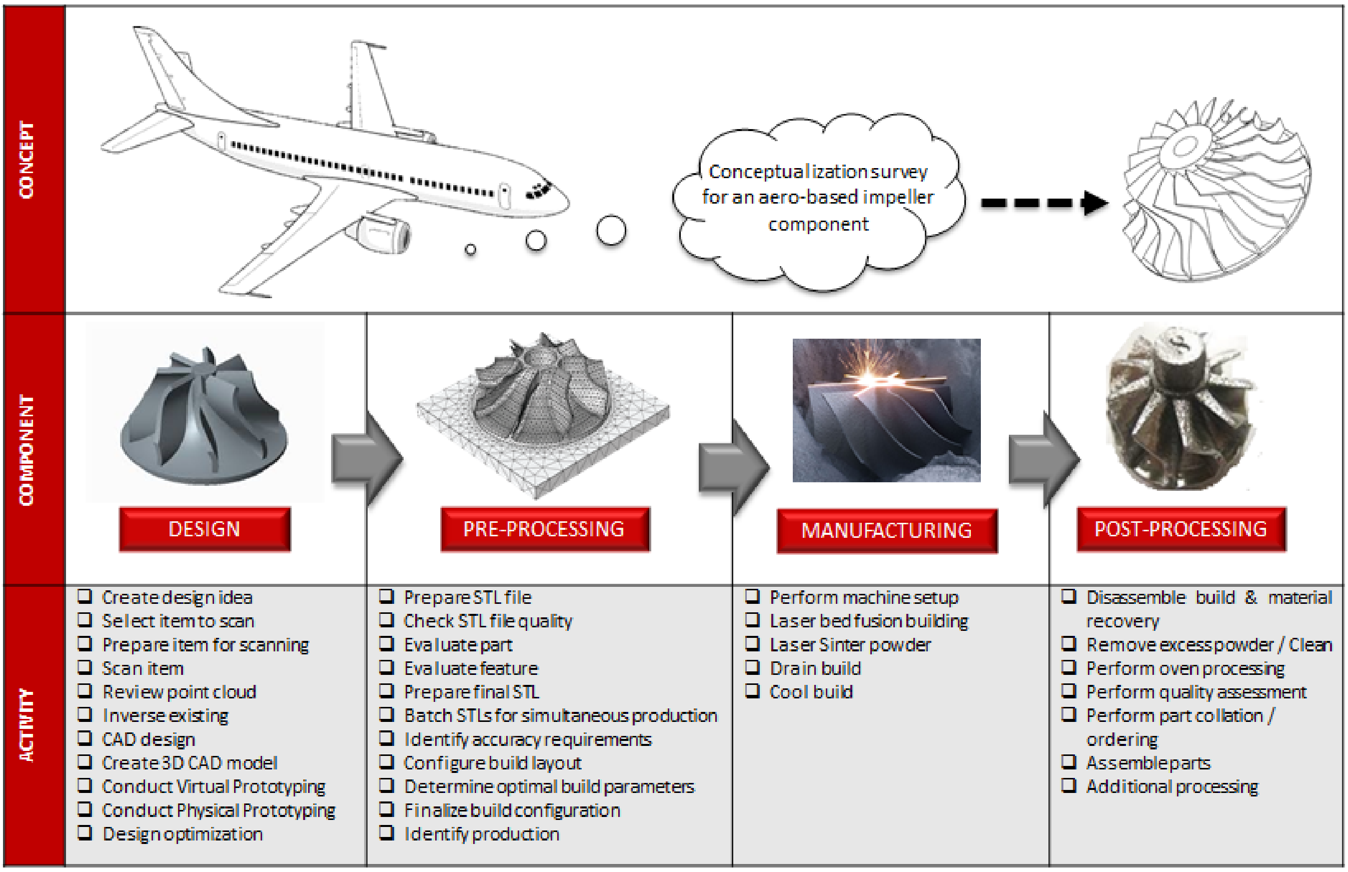

Fig. 3. Design knowledge of a component built through Additive Manufacturing

4. Conclusions

In this article, an integrated approach is provided for additive manufacturing (AM) based on design processes from the Design for Manufacturing (DFM) perspectives by applying Concurrent Engineering principles of Integrated Product and Process Development (IPPD) method used in the development of an integrated decision tools to support design for efficient production in AM techniques. Aiming to explore design possibilities allowed by AM, a practice based research is conducted with the expectation to produce knowledge concerning the design methodology. This developed integrated, lean and tailored GPR approach is needed to provide a comprehensive, standardized strategy to enable AM become a viable manufacturing option.

Without this appropriate design knowledge, it is difficult to fully exploit the potential of AM. Practicing designers can adopt these integrated techniques and may as well influence professional design practice. This study also investigated the current understanding of DfAM in the industry. Hence, provision of empirical evidences will further inform the development of DfAM knowledge and methods while fostering its adoption outside academia. Conclusively, design is seen as a possible, but subjective matter. This study gives another set of interpretations for use by the designers. Thorough understanding of the design process, design methodology, design rules and support system will result to a paradigm shift in the manufacturing ecosystem of today's world.

Acknowledgements

Research support acknowledgements goes to the Department of Science and Technology in collaboration with the Council of Scientific and Industrial Research, (DST-CSIR), and the Research Chairs (Gibela) at the Industrial Engineering Department of Tshwane University of Technology Pretoria, all situated in South Africa.

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