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Design Exploration and Design Exploitation for Additive Manufacturing

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Abstract: *Additive manufacturing (AM) has been widely adopted in the product development stage, and in some specific industry sections such as hearing-aids, orthodontics, and rapid prototyping, AM has become the main manufacturing techniques in their toolkit. The number of industrial AM application has been increasing considerably during the last decade, and AM enabled sustainable manufacturing method is becoming more promising. The major industry giants and academic institutions are investing a significant amount of resources and time on AM and its related fields to expend the AM application portfolio in a real industry production environment. I will introduce a serial of articles about the topic: the design exploration and design exploitation for Additive Manufacturing. A systematic hierarchical research architecture is adopted in this project and is divided into three parts: macro-level design, meso-level design, and micro-level design. The level of analysis structure spreads the research topic into different categories. A list of design principles will unfold Macro-level design research. The meso-design will execute the main techniques for innovative design techniques, and the final micro design research will be mainly focused on the micro-level of design contribution. Along with the development of understanding for DfAM, a multi-disciplinary study will also be conducted in the research involving computational design and simulation, virtual prototyping, machine learning, cost analysis, and practical operations related to AM software and hardware. The content includes the theoretical analysis, various case study and my personal research and development experience. The primary research will be around the center of rethinking the DfAM. The contents will include a background introduction for current (DfAM) Design for Additive Manufacturing status, the importance for the AM industry development, and the current constraints of DfAM.*

Keywords: *design, additive manufacturing, product design, design thinking, DfAM, 3dprinting, engineering design, design education, dfm, design for manufacturing*

1. Introduction

Additive manufacturing, also commonly called 3D printing, is becoming more engaged to the production than 30 years ago, when Charles W created the first Stereolithography 3D printer in the mid-1980 (Charles W, 1986). Currently, there are seven major AM processes present: extrusion, photopolymerization, powder bed fusion, material jetting, binder jetting, directed energy deposition, and lamination. Processes differ in the feedstock format, i.e., a solid filament, sheet, powder, or liquid. The material chemistry and energetics of transformation determine the resultant thermal trajectory of the process and influence the amount of energy required (The seven categories of Additive Manufacturing | Additive Manufacturing Research Group | Loughborough University, 2020). Each AM process has its forming techniques but shares the same layering forming characteristic.

2. The importance and constrains of DfAM

2.1. The importance of DfAM

DfAM includes not only the process inside a 3D printer but the process and supplier chains that involved. In reality, DfAM has a substantial difference between design knowledge, guidance, tools, methods, and process at all levels than traditional DfM (Design for Manufacturing) (Patrick et al., 2018). For instance, the design freedom of AM allows producing the features which are not feasible or too complicated to create by the traditional manufacturing methods. Therefore, DfAM requires its own rules and tools.

Some steps are less vital in AM based production compared to the traditional methods. For example,

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Part consolidation can be achieved by additive manufacturing, which can also reduce the amount of the assembly work. Meanwhile, AM has its own production batch and cost model, so the demand for standard and quality will approach differently (Thompson et al., 2016). Insufficient understanding and knowledge will lead to the limitation and drawback of the AM penetration towards the industry. DfAM has also been cited as one of the technical principle challenges of AM. The design practice and design process should also be different due to the different characteristics of the AM process. Hence, a new knowledge base for DfAM is needed.

2.2. The constraints of DfAM

Hindering factors for the constraints and considerations of AM limit the implementation of AM to design processes. The current AM industry is facing several hindering factors resulting in a lack of exploitation of its promotion and integration.

2.2.1. Lack of knowledge

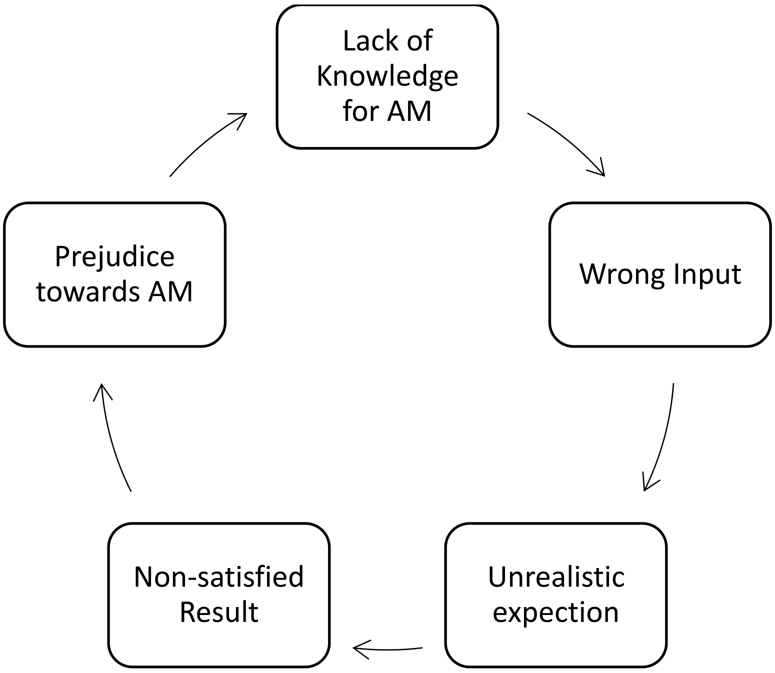

Figure 1 Vicious circle for lacking DfAM knowledge

In the current industrial manufacturing system, AM has a noticeably short history compared with some conventional manufacturing method, for example, John Wesley Hyatt invented injection molding in 1872. Therefore, a systematic study and technology accumulation has been cataloged carefully in the current manufacturer's portfolio. The designer and engineer can refer to exiting guidance and knowledge. Since AM is still a novel manufacturing technology and due to its unique forming method, most of the product designers and engineers do not have enough know-how on the capabilities, benefits, and limitations of AM(Kumke et al., 2017). Current existing design guidelines, rules, and references are still too limited to approach the industrial designer and engineer, and the lack of an industrial uniform standard is also becoming hard to persuade the design department from the OEM to adopt DfAM. The lack of design reference will cause the selection of design and engineering solution are not fit in the AM process, unrealistic expectations, and limit application exploitation. Figure 1 shows the lack of DfAM knowledge will eventually enter a vicious circle for AM development.

2.2.2. Restricted Design Mindset

As AM has the reverie of design freedom, most people are excited by this novel technology. However, It is hard for designers to discover an affective approach when they are starting DfAM. In the current education, the engineering students' major coursework focuses on problem-solving, design specifications, meeting requirements, and avoiding failures. The designers are taught to embrace ambiguity, uncertainty and challenge the assumptions and constraints for any problem they face. They search for opportunities while engineers satisfy constraints. The same thing seems to happen in the industry, although it manifests in a slightly different way. The experience of part design for machining

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(or forging or casting) has intimate knowledge of the constraints associated with that process and have a tough time letting go of that knowledge to embrace the design freedoms of AM(Simpson 2019).

Creativity restrained obstacles raise the challenge of exploring the potential of AM. When the designers are dealing with most of the design tasks for the conventional manufacturing method, the previous tasks are available, or in some cases, they are identical. Designers will avoid using alternate solutions or ideas, which can be referred to as the design fixation. However, for DfAM tasks, if the design creativity is limited or minimized in order to refer to the preliminary design for other production techniques, it will typically lead to a design failure. Figure 4 presents the convention engineering features appeared on the AM parts, which results in extensive use of supporting material.

2.2.3. Process barrier

The process barrier reflects the fundamental differences between the traditional manufacturing process. In most industrial production scenarios, the decisions for components are normally made in the last stage of design development with its corresponding manufacturing methods. While AM is a predefined manufacturing technology, it is not possible to revise the production method at the end of the loop and realize the benefit of AM. Since the AM process is focused more on the global picture of the product instead of a single component, the design implementation will need to consider in the beginning and all through it's end of product life cycle.

As the most of industry have been using the conventional development process for an exceedingly long period, the divergence between AM and other conventional manufacturing technology lead AM to be accessed to produce the conventionally designed parts (Thompson et al., 2016).

3. Research Methodology

The Design Exploration and Design Exploitation are based on three levels of study with three different analysis levels, Macro, Meso and Micro level. Figure 2 presents the main structure of this three level DfAM approachs. The key difference in this structure is the focused area. The benefit of this study structure is the expend-ability in both horizontal and vertical direction.

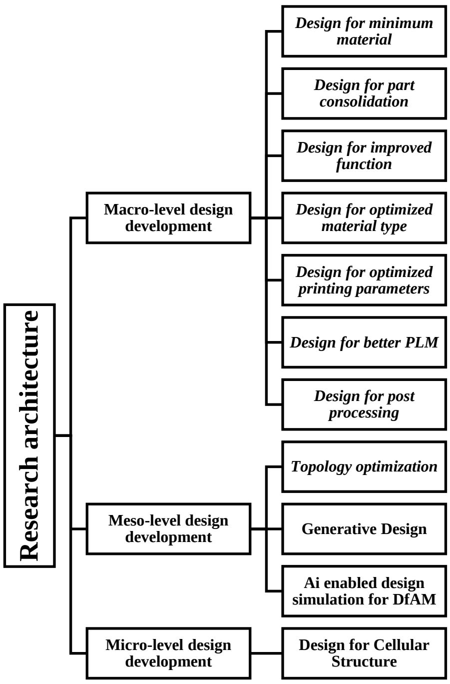

Figure 2 Research Methodology

3.1. Macro-level design development

Additive manufacturing (AM) is envisioned to change how products are developed, produced, and delivered to the consumer across the global landscape. Throughout the product life cycle, AM will become the tool to enable designers and engineers to improve their computational design, and the

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design principles will be developed along with this process and will become the essential reference and guidance.

3.1.1. Design for minimum material

Optimizing the design in order to put the material to the place where the force is applied, additional wasted material would not be needed in the first place. Use tools such as topology optimization and lattice structures to make lighter and more efficient products.

3.1.2. Design for part consolidation

The AM process is, therefore, toward the end of the product development process, and the design does not need to consider alternative manufacturing processes, which means that if the part assembly can be simplified using AM, then this should be done. For example, it is possible to build fully assembled hinge structures by providing clearance around the moving features. Besides, complex assemblies made up of multiple injection molded parts, for instance, could be built as a single component. Thus, when producing components with AM, designers should always look for ways to consolidate multiple parts into a single part and to include additional part complexity where it can improve system performance (Gibson, Rosen and Stucker, n.d.).

3.1.3. Design for improved function

The ability to create complex geometry and shape will allow designers and engineers to explore their creativity towards their products' functions. Geometry improved function design can be achieved by several methods; for example, adding the conformal cooling channels for injection molds can achieve better cooling efficiency for the injection molding process.

3.1.4. Design for optimized material type

Explore the possibilities of 3D-printing a part in a material that is traditionally difficult to machine or form, to gain the benefits of better material properties such as thermal conductivity, malleability, or strength. Consider not what material the part has been made of in the past, but rather what functions it must perform and then choose the most suitable available AM material.

3.1.5. Design for optimized printing parameters

AM is a typical long process manufacturing process regarding the processing time inside the machines, compared with other manufacturing methods, such as injection molding, metal stamping, metal casting, and thermo-forming. Pre-process, and in-process control is considered particularly important.

Understanding the process control and parameters when designers create the digital data for the AM process will benefit all the production chain. For example, the support structure generation can be reduced or eliminated if designers take the overhang angle in the consideration at the first stage.

3.1.6. Design for better PLM (Product Life cycle Management)

All tasks involved in the production of an AM part, from pre-process, process monitoring, to post-processing are traceable. Easy accessibility of the complete product knowledge is providing an opportunity for all practitioners during the whole product life cycle. Product design optimization and iteration will become realistic in any stage of product development. Furthermore, the ability to quickly adapt manufacturing parameters, as enabled by AM technology, according to feedback from later life cycle stages, encourages to rethink the common design process. Instead of relying on generalized design guidelines, developers can access product behavior and manufacturing process data, and from there derive product-specific design knowledge (Müller, Panarotto, Malmqvist and Isaksson, 2018). Design for better PLM can also benefit the product supply chain and after service maintenance. The track abilities of AM PLM also offer the potential of the mass customization, and each product is designed and traced by its PLM individually.

3.1.7. Design for post-processing

According to the research done by the National Institution of Standard and Technology, post-processing costs account for 4 to 13% of overall production costs, depending on the exact process and materials involved (Thomas and Gilbert, 2020). As with the labor cost example above, post-processing expenditures for both traditional and additional manufactured parts are inevitable and similar. In the development stage, the minimum process design needs to be considered. Some design techniques, such as self-supporting structure, accessible featured design, and stress release structure,

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are being developed for the minimum of post-processing work.

3.2. Meso-level design development

Additive manufacturing (AM) is envisioned to change how products are developed, produced, and delivered to the consumer across the globe. This section will describe the main design tools and techniques which will be applied in this research.

3.2.1. Topology optimization

TO (Typology Optimization) has been existed in the engineering world for over two decades, and it uses a mathematical algorithm to optimize the material distribution in a boundary space with given loads and constraints (Langnau, 2020). Due to the complexity of the objects created by TO, it was not commonly accepted and adopted by the current engineers for the conventional manufacturing methods. Until recently, AM brings in the enormous design freedom into the possibilities of manufacturing, which is not feasible by traditional manufacturers.

On the other hand, the advent of AM also refreshed the optimized possibilities for geometry creation by the modern algorithm. The detailed work-flow is presented in Figure 3.

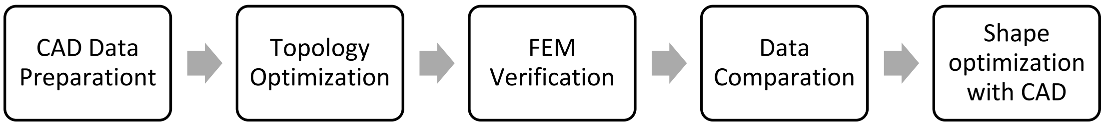

Figure 3 The typical work-flow for Topology Optimization

3.2.2. Generative Design

Generative Design (GD) is a software that can enhance the capabilities of engineers and use cloud computing with machine learning capabilities to explore a whole new set of solutions. It extends the range of effective solutions known to engineers or designers to meet their design challenges.

Generative design can seem like a design exploration process. The boundary requirements, materials, production methods, and potential cost are all defined before starting the GD process. The permutation of possible design solutions will be generated for the designer. The options from the generative platform will also conduct self-iteration to visualize how it achieves the result. Figure 4 shows an example of GD design from General Motor and the GD work procedure.

The input for generative design is like that of many optimization tools. However, generating a design includes many effective (high-performance but cost-effective) designs or solutions, rather than an optimized version of a known solution.

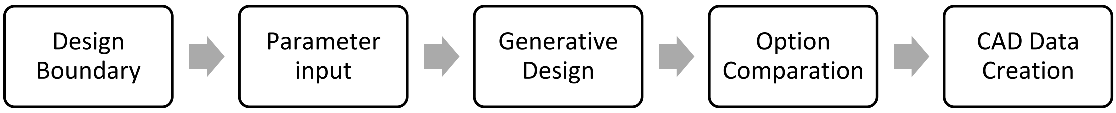

Figure 4 The standard workflow for Generative Design

In addition to creating entirely new solutions, another area where generative design is different, that it considers manufacturability, which means that the process of testing the product and returning to the drawing board is greatly reduced. Traditional optimization focuses on improving known solutions, which usually involve removing excess material without knowing any product manufacturing or usage methods. Finally, another modeling, traditional simulation, and testing steps are needed(What is Generative Design | Tools & Software | Autodesk, 2020).

The concept AI (Artificial intelligence) based machine learning model will be implemented into GD process. It is also the current trend of GD development. The goal of this model is to add more design perspectives inside GD, such as generating support structure, infill lattice structure, and eventually, the GD model should also be able to produce the desire printing parameters. Besides, AM cannot be treated as one single technology or process, and it is a group of technologies that shared the same forming characteristic. So the generative design AI model should also take the variations between each technology of AM into consideration.

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In the future, GD may become not only a design innovative accessorial tool but also a specific design process in DfAM.

3.2.3. Ai enabled design simulation for DfAM

The flexible manufacturing process of AM has been driving several new simulation technologies, and this research will include the most common geometry-based simulation and process-based simulation.

3.2.3.1. Data processing (pre-process) simulation

Determining if a model is printable or not is a common question in front of engineers when they are facing AM. Even with the help of some assistant software, such as slicing software and meshing analyzing software, the final decision will have to be based on engineers' experience and knowledge. (Jee and Witherell 2017; Mani et al. 2017)

This determining method is often time and labor-consuming, and the error rate is also hard to control due to the background and experience difference from different engineers. Hence, a systematic and automatic geometry analysis and simulation are essential for DfAM in order to achieve the standardization of AM.

With help from current machining learning technology, simulation software will be able to gather the human experience and classify them into a digital catalog. This system will be able to give some suggestions and eventually replace the human process for geometry analysis.

3.2.3.2. In-process simulation

Many major engineering solution software companies are developing Process-based simulation, and many of them are adopting the artificial intelligence model with the traditional FEM simulation algorithm.

3.3. Micro-level design development

3.3.1. Design for Cellular Structure

The concept of designed cellular structure is motivated by the desire to apply materials only to where the force is applied or require specific functionalities, such as energy absorption, thermal and acoustic insulation. The complexity of cellular structure makes it difficult to generate by the current manufacturing method. However, AM technology, especially laser-based technology, such as SLA, SLS, and SLM, offer a possibility to create these complex cellular structures.

The cellular structure can be divided into two parts: stochastic structure and non-stochastic structure. Stochastic structure commonly refers to a foam structure, including open and closed foam, for example, Voronoi structure. In AM, the most used are the non-stochastic structure showed in Fig. 5, i.e., lattice structure (Raymont et al., 2011).

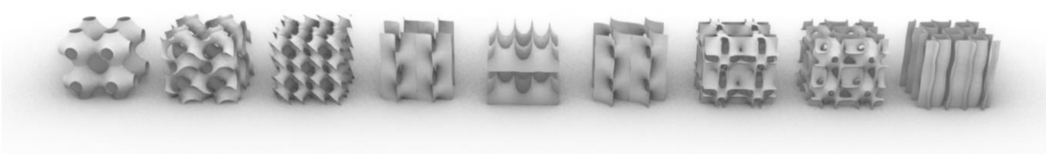

Figure 5 TPMS(triply periodic minimal surface) created by parametric tool Grasshopper

Cellular lattice structures have previously been created using traditional commercial CAD packages. However, these packages have proven to be unsuitable for potentially large complex micro-architectures. Commercial tools for 3D latticing are becoming more widely available, as it is not trivial to create a 3D lattice in a CAD system, and a large number of unit cells requires an efficient data structure. Commercial software packages, including Autodesk Netfabb and Altair Inspire, can generate lattice structures as a way of locally grading material density.

4. Conclusion

In comparison with the traditional manufacturing process, for example, injection molding, manufacturers can produce a significant amount of parts in a short time, but meanwhile, they need to invest both time and capital in tooling. The method of additive manufacturing, in contrast, is building an object layer by layer from the digital data without any tooling investment. In reality, the additive manufacturing process including design constraints and several manufacturing steps. In order to make the final parts succeed, the right material choice, suitable printing technology, design instructions and post-processing methods need to be considered from the beginning.

Design tools for additive manufacturing are becoming widely accessible and more user-friendly than before. All these encourage the application users feel confident to adopt AM in their production system. More industrial applications represent the move of AM technologies from the rapid prototyping to industrial production.

However, the development and investment for AM on research are not evenly distributed inside the AM technology loop. Research on AM is broadly covered in the fields of materials, software, and new processes. Despite a growing body of knowledge concerning the technological challenges, the limited research has been performed on the methods that allow designers to deal with this game-changer (Doubrovski et al., 2011).

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