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A Bottom-up Design Framework for CAD Tools to Support Design for Additive Manufacturing

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Abstract. Additive manufacturing (AM) technology is enabling a platform to produce parts with enhanced shape complexity. Design engineers are exploiting this capability to produce high performance functional parts. The current top-down approach to design for AM requires the designer to develop a design model in CAD software and then use optimization tools to adapt the design for the AM technology, however this approach neglects a number of desired criteria. This paper proposes an alternative bottom-up design framework for a new type of CAD tool which combines the knowledge required to design a part with evolutionary programming in order to design parts specifically for the AM platform.

1 Introduction

Research and development progress in additive manufacturing (AM) technologies has given rise to an increased output of functionally usable parts. There are a number of advantages to AM in comparison to conventional subtractive manufacturing techniques, such as milling, turning or drilling, including increased shape complexity, functional complexity, material complexity and hierarchical complexity, [1] which are resultant from a layered manufacturing process.

AM does not however, come without disadvantages. There are limitations and constraints including the size of the build geometry, a slow build speed, support structure requirements, residual stress considerations, and post-processing requirements for functional surfaces. A skilled and experienced designer can mitigate against a lot of the aforementioned limitations but there will always be a compromise between the selection of additive and subtractive methods.

The ability to manufacture practically any shape, regardless of complexity has allowed the designer to build complex freeform surfaces and also optimize designs for particular criteria, such as reducing weight or increasing stiffness. Computational support is required to perform these structural and topological optimization processes and the final designs often look very different to the initial CAD models proposed by the designer during the embodiment phase.

The current top-down approach of designing a part with conventional subtractive manufacturing techniques in mind and then topologically optimizing the design for an

AM platform leads to an increased development time of a final part suitable for manufacture and the resulting designs are not developed for all criteria that is required for a functional part.

In contrast to a top-down approach, bottom-up approaches seek to commence a part design with the manufacturing platform in mind; for the AM platform the designer will consider the design for additive manufacturing (DfAM) rules throughout the part design process. There are a number of challenges to altering from a top-down to bottom-up design mentality, particularly in terms of computational design support.

This paper will discuss the requisite criteria that a designer has to consider when designing for AM. Secondly, it will explore the benefits of developing a design strategy for bottom up development for AM, and finally, a theoretical CAD framework for designing for AM will be hypothesized and proposed.

2 Review of Design for Additive Manufacturing

Before it is possible to develop a new framework for DfAM it is necessary to consider existing work in defining design rules across multiple AM platforms and also in computer aided design tools for AM.

2.1 A Review of Existing Design Rules

In order to establish the limitations of the AM technologies, a number of researchers and AM machine manufacturers have investigated the development of design guidelines and design rules for various platforms in order to help the designer create parts that have a higher chance of a successful build. Guidelines have been produced for Fused Deposition Modelling [2, 3], Selective Laser Melting [4], Direct Metal Laser Sintering [5–8], Stereolithography [9], Electron Beam Melting [10].

These design rules are specific to processes and are also often specific to machine setups and calibrations; as such industry and makers often create their own set of design rules which enhance the capability of their particular machines. In addition, the design rules are focused primarily on the manufacturability of the part. In reality, the manufacturability is only one element of the design process and it is important to consider other elements in the incorporation for component design rules. Furthermore, these ideas require consolidation onto a platform in which they can be used to aid the designer during the product design process.

There have been a number of papers highlighting redesign for AM case studies, Becker et al [11] proposed a redesign strategy for a mix device following the creation of basic design guidelines, reducing the number of parts and minimizing assembly time. Another example of part redesign involved the redesign of a bracket for manufacturing using an EBM process [12]; through parametric optimization and structural validation the authors were able to improve the manufacturability of the product on the AM platform.

2.2 A Review of Additive Manufacturing Computer Design Tools

AM computer aided design tools can be split into two categories: top-down and bottom-up CAD tools. Top-down methods aid the designer after they have developed their final design solution. These include tools for assessing the manufacturability of the part [13], suggesting the most suitable additive process [7], or aiding in material selection for the part [14].

Alternatively, bottom up CAD tools help the designer to explore the design solution space and generate designs based on the specified input criteria. Bottom-up CAD tools can also be referred to as generative design tools. Research into generative design tools has been used to design architectural structures [15], and a generative design tool has been proposed for part design based on user specifications [16].

There is also one example of a tool which exists between these two regions. Krish [17] proposes a tool which will generate further solutions based on the original computer model developed by the designer. Results show that it is possible to use native CAD systems for design exploration, however the size of the search space is limited using this method.

3 Framework for a New Additive Manufacturing CAD Tool

Building on the literature review for current design rules, it is necessary to consider how these rules can map into computation design support tools to aid the designer. A proposed theoretical framework will now be presented.

3.1 Additive Manufacturing Design Considerations

The AM design rules discussed in the literature review (section 2.1.) have helped the designer to understand the limitations of the machines and the manufacturability of AM parts. It is now important to develop these design rules into a format which can directly support the designer throughout the design process.

Table 1 shows the design considerations which are necessary for the designer to consider during the development of the final part design. The considerations have been divided into process and geometric considerations. In order to successfully design for AM both categories must be considered equally during part design.

Table 1. Selection of process and geometric considerations when designing a part

Process Considerations	Geometric Considerations
Build strategy	Functionally graded materials
Build orientation	Dimensional accuracy
Residual stresses	Part consolidation
Support strategy	Optimization techniques
Layer thickness	Strength
Production Speed	Stiffness
Surface quality	

The cognitive burden on the designer can be demanding as a vast number of qualitative and quantitative considerations have to be considered during the conceptual and embodiment design stages. The design considerations in table 1 can be subdivided into quantitative and qualitative categories. Quantitative rules make use of physical laws and can be defined using equations and algorithms. They are extremely useful in defining the product design specification as they can be used as metrics to evaluate the success of the final design.

Qualitative considerations, on the other hand, cannot be defined using mathematical techniques, they are instead based on the designers experience and common sense reasoning. This tacit knowledge is difficult to capture, however qualitative design considerations are paramount to the development of parts and products that humans will enjoy interacting with, developing product families and ensuring company design regulations are incorporated into a design.

In addition to the design requirements, the designer also has to be aware of the manufacturing methods which are available and also the limitations of these processes. Typically, the designer will have a limited number of manufacturing machines available. It would be beneficial for the designer to specifically design parts for the available resources. Table 2 shows a non-exhaustive list of the design considerations a designer may have to scrutinize in a typical part design.

Table 2. Design considerations which may be required and traded-off against one another when designing a part

Quantitative	**Qualitative**	**Available Resources**
Support strategy	Testing requirements	Additive process
Build orientation	Maintenance strategy	Subtractive process
Build quantity	Inspection routine	Inspection process
Stress analysis	Aesthetics	Materials available
Geometry	Human-part interface	Post-processing tools
Layer thickness	Recyclability	
Cost	Ergonomics	
Mass		
Temperature range		
Humidity range		
Interfacing components		
Machining cutting forces		

The proposed CAD tool framework will have to help the user develop the problem space and consider the manufacturing constraints on the system when proposing the design solutions. Furthermore, the design tool must help to remove the cognitive burden on the designer by reducing the number of design considerations that must be examined.

3.2 The Role of Computation in Design for Additive Manufacturing

The development of computer-aided-design tools has led to designs of far greater complexity. The ability to make rapid changes to designs, or achieve feedback on a design from another person at a click of a button has decreased product development time. Interfacing part modelling software with analysis tools such as finite element analysis, and computational fluid dynamics also allows verification of designs computationally, reducing the amount of wastage, both material and time, from manufacturing unsuccessful prototypes.

Whilst CAD systems have doubtless increased productivity and improved design output they are not without flaws. The disadvantage of CAD systems have been explored by Robertson and Radcliffe (2009); traditional CAD modelling tools can lead to a reduction in creativity throughout the design process. Three critical limitations to current CAD systems will now be explored.

- Circumscribed Thinking: The complexity of the design that is created is proportional to the designer proficiency in the modelling tool. The design output from the designer is currently limited by their knowledge of the CAD system as opposed to their cognitive creative output. This has huge implications when designing specifically for AM. The shape complexity, part consolidation, and optimization techniques which are required to optimize parts for AM require expert level skills in the CAD system to be able to develop designs which exploit the full potential of the machines. Designers will have to develop years of experience on the modelling tools before they can begin to design parts which are optimized for the AM process.
- Premature fixation: As computer models become more complex the designer feels less incentive to make major design changes. This circumstance tends to occur in less experienced designer rather than expert designers, however, typically there will be changing requirements throughout the design process. The ability to develop designs which balance a vast number of design criteria by exploring the extensive solution space is imperative to exploiting AM technology.
- Cellular structures: AM machines can print at various levels of hierarchical complexity. The features can be designed with shape complexity across multiple scales [1]. Honeycombs, lattices and other shape elements can be designed into a part for weight reduction and to demonstrate variable properties across a part using one material. Depending on the size and shape of a part the amount of cellular features may be in the order of hundreds of thousands; traditional CAD systems cannot perform geometric modelling on this number of geometric elements.

In order to alleviate a number of the aforementioned problems a new framework for a CAD tool will be explored.

3.3 CAD Support for Bottom Up Design for Additive Manufacturing

It is becoming clear that designers require some degree of computational support in order to take full advantage of AM platform capabilities. However, it is not yet clear as to the level of support that is actually required. The four categories below shows the variance of human/computer interaction (HCI) that are possible; moving down the categories there is a clear shift from top-down to bottom-up design strategy. Fig. 1 depicts the mapping of varying levels of HCI onto a continuous scale.

1. Designers use the CAD tool as they see fit, however, the CAD system does not give any user feedback on the design or manufacturability based on any defined requirements. The designer can then choose to analyze the design in external programs. This is the current standard for computer aided solid modelling for AM.
2. The designer proceeds with CAD in the detailed stage, however, there is an addition to the CAD system which allows the designer to select an option for a computer program to evaluate certain criteria or give advice on which process best suits the part. This is a prime example of top-down design and it is the current state-of-the-art.
3. The designer defines a set of inputs which are fed into the computer algorithm to generate a set of design solutions. Incrementally the designer evaluates the design solutions which have been given and these inputs are then used to define the next set of design changes. The more iterations specified by the designer the closer algorithm will get to the specific user requirements [19]. This is an example of generative design technology and moves into the bottom-up design bracket.
4. The designer defines the input parameters of the system. A computer algorithm will then generate all possible solutions that fit the design requirements. From the initial results, the algorithm will evaluate the best solution depending on the optimization criteria specified by the designer. The output of the algorithm will give the designer one option which will be optimized for a particular function. This is an example of autonomous design. The principal challenge of fully autonomous design is that it is impossible to capture all of the qualitative, tacit knowledge that the designer possesses and as such the output designs will not cater toward human interaction.

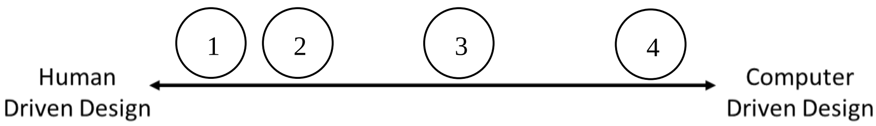

Fig. 1. Levels of HCI that are possible in CAD systems

Whilst the second level of HCI is useful for the evaluation of a design, it does not solve the aforementioned issues surrounding top-down design. The most sensible proposition for new CAD tools must therefore be the third level; a method in which an algorithm creates a design, however the design inputs are driven by the designer. This design method will now be explored further with a proposition of a new generative CAD tool framework.

3.4 A Collaborative Generative CAD Tool for Additive Manufacturing

The generative design framework can be described by three interlinked stages as shown in fig.2. The primary stage describes the development of the problem space. The proposed CAD tool incorporates a series of databases of criteria which may be specific to the part. The databases include the design considerations shown in tables 1 and 2 and could also contain company specific parameters to ensure design continuity throughout an enterprise.

The designer is then required to extract the relevant design parameters from the databases. One of the challenges in AM that requires attention is the understanding of the trade-offs in the technology. Consider a design which is optimized for weight reduction and as such a lattice structure is employed in the design, whilst this is appealing and solves the weight issue, the part becomes challenging to inspect and cannot therefore be certified for use as a functional component. The designer will have to create a hierarchical structure of priorities they desire for the design.

The designer then determines the machine and material availability for additive, subtractive and post-process technologies in order to develop specific solutions for these technologies. This is important as optimized designs will be based on specific material and machine combinations.

A design solution volume is defined as the volume to which the generative software can apply material. From this information a generative algorithm can be used in conjunction with optimization techniques to deposit material within this solution volume.

The second stage of the framework is termed solution development. Here solutions are developed which are optimized for the trade-offs selected from the hierarchy stated in the previous stage. At this stage in the concept generation, it is solely the quantitative parameters which will be considered.

By taking advantage of multi-criteria evolutionary algorithms the designer can program many inputs into the system, with the design evolving within the solution space converging as close as possible to the criteria hierarchy intended by the designer. At this point the designer has the option to impart some of the qualitative knowledge they possess with regards to part aesthetics and human interaction with the part. The designer will also have the opportunity to vary input parameters from the databases in the primary stage.

The CAD tool will then use the best solution(s) as selected by the designer from the first generative stage as the new evolutionary input(s), generating more appropriate designs based on the modified input parameters and defined qualitative information improving the capture of the designer's initial intent. This approach is then repeated, within a user feedback loop, until a satisfactory design can be delivered from the system. The ability and speed of recompiling design solutions is integral to the system. The overall quality of the design solution is dependent on giving the designer the ability to redefine the problem space as more knowledge is gained about the design direction.

The final stage of the framework is labeled design output. In order for the design tool to be useful the design would have to be exported in files types currently used in AM, e.g. .STL, .AMF. in conjunction with the AM file formats the tool should also give some indication of the correct build orientation and build strategy along with suitable post-processing techniques in order to finish with a functional part.

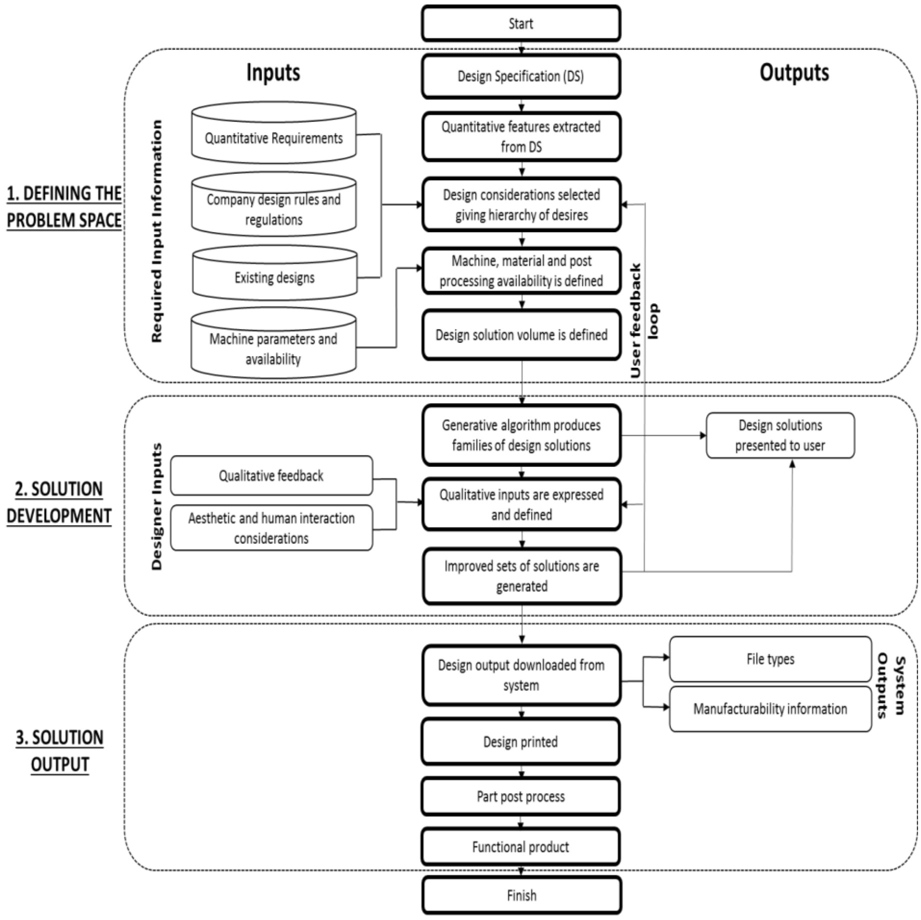

Fig. 2. Schematic of the proposed CAD framework including relevant system and designer inputs and outputs.

3.5 Disadvantages to Bottom-Up Design Methods for Additive Manufacturing

Whilst a bottom-up design approach would give the designer a much greater scope when designing for AM, it is important to consider the potential drawbacks of using this approach. Firstly, bottom-up design is not suitable for all design applications. Consider the design of a turbine blade for the aerospace industry, many decades of development have shaped the design of a turbine blade and it would be more suitable to design this component from a top-down approach in order to rapidly converge on the optimum solution.

Secondly, HCI is necessary for the generative design tool however, human input also leads to a reduction in speed of the algorithms and also a lack of consistency in design selection. It would be impossible to generate learning algorithms if the user defined the same result with a different satisfaction rating across multiple iterations [19].

4 Conclusions & Future Perspectives

This paper proposes a shift in thinking from top-down to bottom-up design methodology with particular emphasis to AM. Whilst a bottom-up approach to design will not be suitable for all design applications, systems which require optimized shape design for different categories, the proposed bottom-up design methodology may provide improved solutions when designing for AM.

Building upon current research, design inputs required to successfully design a part for the AM platform have been assessed and these can be split into process and geometric requirements, in order to gauge the feasibility of employing these criteria into a design tool, they were further split into qualitative and quantitative considerations. It was deduced that the proposed CAD framework would have to utilize both human and computation knowledge to develop a viable solution to a component design problem.

By considering the advantages different levels of HCI, a new theoretical CAD framework has been proposed which aims to exploit the advantages of AM technologies whilst alleviating some of the disadvantages that exist with using conventional CAD tools during the design process. By encouraging the user to define the correct hierarchical problem space and employing advances in multi-objective evolutionary computing, the designer will be able to search greater areas of the solution space and generate more appropriate and satisfactory design solutions.

Whilst a new AM perspective has been defined in this paper, further work must be undertaken before this kind of design tool is applicable for complex three-dimensional part design. Experimental work has to be undertaken in order to establish a full set of part design requirements for the system knowledge database, alongside developing methods for capturing design information from existing designs. Furthermore, defining the relationship between machine parameters and their effect on a final part must be defined.

Evolutionary models need to be optimized for design in order to be able to fully explore the solution space and new ways of utilizing these algorithms for the generation of three-dimensional part design need to be established.

It is acknowledged that there are many issues that need to be addressed before this kind of tool can be used effectively, however, the framework in this paper can be seen as a possible method of improving a designer’s ability to capture and utilize the full potential offered by emerging AM technologies.

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