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CROWDSOURCED DESIGN PRINCIPLES FOR LEVERAGING THE CAPABILITIES OF ADDITIVE MANUFACTURING

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Abstract

The proliferation of additive manufacturing technologies has inspired its use at different scales for both prototyping and production. Moreover, the accessibility of inexpensive machines has enabled design at the end-user level. However, the unique capabilities of these layer-based manufacturing processes are often underutilized or even unexplored. In this work, the authors leverage a crowdsourced repository of additive manufacturing design data to extract useful design principles for additive manufacturing. Herein, 23 design principles are discussed from said extraction. Many of the 23 principles are found throughout the literature. These lend validity to those that are novel and not yet existing in literature. It is found that the 23 principles range in specificity in how they relate to the manufacturing process The levels of specificity from most general to specific include (i) design for manufacturing, (ii) design for digital manufacturing, (iii) design for additive manufacturing, and (iv) design for fused filament fabrication. The principle, when implements can help designers to fully leverage the capabilities of additive manufacturing technologies.

Keywords: Design for X (DfX), Collaborative design, Additive Manufacturing

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1 INTRODUCTION

Generally defined, additive manufacturing (AM) represents layer-based manufacturing processes that selectively place material according to a digital representation of an artefact (Gibson, Rosen, et al., 2010). AM has largely enabled direct digital manufacturing and altered the way designers approach product and systems design. Rapid prototypes, complex geometries, and highly customizable components are some key capabilities enabled by the technology. Beyond these tangible capabilities for industry, consumer-level AM processes such as fused filament fabrication (FFF) have enabled design by end-users. FFF is an extrusion-based deposition method which patterns and fuses molten polymer at each layer. The technology is widely adopted by hobbyists and similar users because of its low cost, material availability, and small form factor. The widespread adoption of FFF, coupled with online design sharing platforms such as thingiverse.com, has generated a wealth of design data from which useful design insights and guidelines, such as AM principles, may be extracted. These principles can aid designers to fully leverage the capabilities of AM, as they offer many advantages not possible with conventional manufacturing processes.

The focus of the research reported here is the systematic extraction of design principles from empirical data sources, such as thingaverse.com. We consider a design principle to be an actionable guideline that, given a certain design goal, improves the likelihood of success (Hölttä-Otto, 2014). Therefore, well-defined design goals and the application of relevant design principles are beneficial to the design process.

This paper presents design for AM principles extracted using crowd-sourced design data from thingiverse.com. The website is an open platform for the development and sharing of additively manufacturable artefacts online. Thingiverse also provides a genealogical tree of the 3D objects, where subsequent designs based on a preceding design are linked and called *remixes*. Assuming that a remix is created to improve upon the design of its predecessor, the generational changes reveal this improvement as a result of deliberate or inadvertent application of design principles. By observing these modifications, design for AM principles can be extracted.

2 EXTRACTION METHOD

2.1 Crowdsourced design repositories

The principles presented in the work are the product of principle extraction from the crowd-sourced repository of design data Thingiverse.com. Thingiverse exists at the nexus of digital manufacturing, the maker culture, and the Internet (Makerbot, 2014). The website is an online repository for digital manufacturing files where users can share and modify designs. The site is predominantly adopted as a platform to share .STL files. While .STL is the standard for AM technologies, it is also understood that these files are most often intended for use with FFF technology in the context of Thingiverse. FFF technology is predominantly used among Thingiverse users because of its low cost, material availability, and small form factor as previously mentioned.

Other sites such as Sculpteo and Shapeways present similar data, although neither is as open as Thingiverse (Sculpteo, 2014; Shapeways, 2014). Users of these alternative sites purchase designs, which are then additively manufactured by the site operators using a range of selectable AM technologies. The actual .STL files are never exchanged or modified as with Thingiverse. Moreover, Thingiverse provides basic metrics for identifying artefact popularity and utility. These metrics include the number of people that have liked, made, or *remixed* an artefact. These metrics make Thingiverse a better choice for design principle extraction and analysis. *Remixes* are new parts made by modifying an existing artefact. This relationship is illustrated in Figure 1.

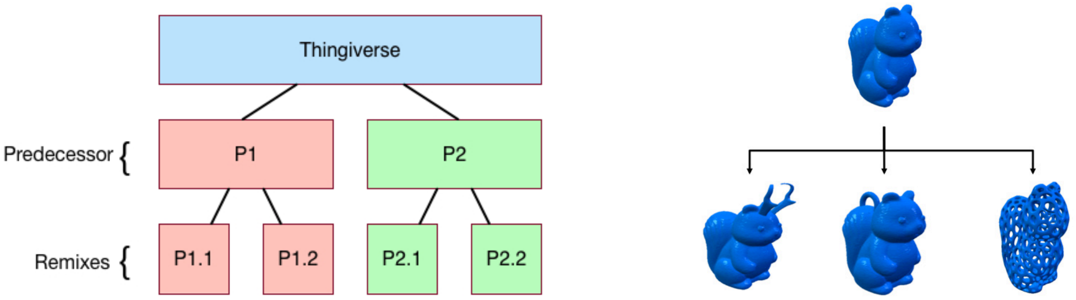

Figure 1. Genealogical hierarchy of Thingiverse artefacts

As of June 2013, Thingiverse claimed to host over 100,000 unique designs. While likely comprised of artefacts made by persons with a wide range of expertise, including novice designers, there exist valuable lessons in design for additive manufacturing. The idea of crowd-sourced design is not itself novel. Recent work has also pointed to the use of online communities as a source of potential design principles (Camburn et al., 2015). No works however have leveraged online components libraries specifically for the extraction of design for additive manufacturing principles.

2.2 Method

In order to extract quality design principles from Thingiverse, we propose the following inductive research method (Blessing and Chakrabarti, 2009). The underlying assumption of this method is that, on average, the changes users make to existing artefacts are intended to improve some aspect of the original. Analyzing the rationale for these changes provides a pool of design principles applied by the Thingiverse community.

The process begins by collecting hundreds of the "most popular" artefacts as ranked by Thingiverse. Popular artefacts were chosen based on indirect correlations to part design and quality, such as high rating of user-based metrics (i.e. number of likes, remixes, and downloads). From this set of artefacts, only those older than six months were retained. It is assumed that Thingiverse's popularity algorithm is sensitive to time. Thereby the six-month requirement filters young artefacts where apparent popularity may be a result of high sensitivity to noise in voting. Finally, the number of downloads metric is used to find which components the community identifies as particularly valuable. For this study, the resulting set of artefacts contained 67 predecessors' artefacts with 272 unique remixes.

This pool of predecessors and remixes is divided and distributed amongst three expert-level raters who have had advanced knowledge in design science, artefact design, and at least minimal expertise in AM. These investigators are instructed to study the artefacts and record any observed changes between predecessors and remixes. Upon collating all observed changes across all three raters, the investigators plus an investigator with expert knowledge in the field of AM performed an affinity analysis across all changes (Otto and Wood, 2001). The resulting groupings are used to derive an AM principle representing each group of categorization (Singh et al., 2009). These principles are presented in the following section.

3 DESIGN FOR ADDITIVE MANUFACTURING PRINCIPLES

In accordance to the prescribed research method, potential design principles are identified from an analysis of changes in 272 remixes from 67 unique predecessors. The investigators extracted a total of 23 unique design principles from the affinity analysis. It is recognized that the approach, especially in using affinity diagrams, is only one of several possible approaches for carrying out this categorization analysis (Keese et al., 2007; Rajan et al., 2003; Stone et al., 2000). For the purposes of this paper, affinity analysis is considered as a construct for forming a consensus principle set from the raters, but with refinements and validations of principle categories through future additional studies.

3.1 The Principles

The principles discussed herein are presented in accordance with the methodology prescribed by Greer and co-authors (Greer and Wood, 2002). The principles include (i) the issue(s) addressed, (ii) design context, (iii) recommendations, and (iv) rationale. The principles are presented in Table 1 while a more in-depth explanation of each principle is provided thereafter. Not every principle extracted is entirely novel. Rather the authors suggest that the emergence of design principles that are also found in the literature are expected and provide validity to the others that have not been previously identified. Principles identified in literature contain a citation to the relevant work in their definition.

Table 1. Extracted design principles

1	Preserve small features by printing them in an orientation which requires no support material
2	Preserve surface finish by printing artefacts in an orientation which requires no support material
3	Prevent part warping by minimizing residual stresses
4	Improve print success by orienting a part with the lowest vertical aspect ratio
5	Reduce weight, material cost, and preserve stability by replacing solid volumes with cellular structures
6	Eliminate assembly steps and time by printing functional joints and interfaces directly
7	Integrate additional functionality by incorporating components or features in unused internal volumes
8	Enable custom processes (i.e. low-medium volume production) by identifying features that are complex or require high levels of user-based customization
9	Achieve desired mechanical properties by tailoring the geometry of the mesostructure
10	Reduce print time by orienting the shortest dimension parallel to the slowest fabrication direction
11	Ensure printability by scaling artefacts and removing non-critical volumes
12	Improve accuracy of critical curves and profiles by orienting critical curves and profiles in the plane of highest resolution
13	Satisfy alternative functional requirements by scaling the artefact
14	Satisfy different parametric requirements by scaling the artefact
15	Minimize design time and effort by reusing already-designed component geometry
16	Leverage the capabilities of the selected AM technology by using comparably high resolution .STL files
17	Accommodate different AM technologies' capabilities by using high-resolution .STL files
18	Improve printability by designing with the resolution limitations of the selected AM process in mind
19	Add function(s) to artefacts by incorporating functional features into non-functional aesthetic models
20	Minimize assembly time and number of components by incorporating snaps fits when possible
21	Reduce production time by standardizing the assembly process
22	Incorporate existing low-cost components by integrating the necessary standard interfaces
23	Improve manufacturability by dividing artefact into smaller components

Based on the findings in Table 1, the principles are now defined and explained, with exemplars of a number of the principles. It should be noted that, as expected, that these principles are not mutually exclusive nor may all principles be applied simultaneously (Palani, et al., 2003; Singh, et al., 2009). Instead, the principles are goal directed and may cause contradictions in certain cases. Some may also apply different solutions to different issues or conversely the same solution to different issues.

1. Preserve small features by printing them in an orientation that requires no support material
With many AM technologies, support material removal imposes stress on the features to which it is adhered. As a result, small features can be easily degraded or destroyed during the removal process. Simply reorienting an artefact in the build tray so that there is no need for support material can preserve the desired small features.

2. Preserve surface finish by printing artefacts in an orientation that requires no support material
Support material removal may impose stress on an artefact. When the material is removed, it also can degrade the surface finish of the artefact. Therefore, artefacts that require better surface finishes should be oriented in a manner that does not require support material (Fig. 2).

Figure 2. Half of a flute is reoriented so that support material is used only on the inside to preserve the outside surface finish of the artefact (Principle 2)

3. Prevent part warping by minimizing residual stresses
In a layer-based manufacturing process, residual stresses can accumulate over many layers. This accumulation can induce part warping and even separation from the build tray. Minimizing or eliminating residual stresses in the artefact can mitigate this phenomenon. This mitigation can be done by and avoiding excessive material in the layer plane for instance by using an nonsolid model (Gibson, Rosen, et al., 2010).

4. Improve print success by orienting a part with the lowest vertical aspect ratio
Residual stresses in a part will often build up in an additive fashion over many layers (layers tend to contract as they cool or cure). These residual stresses can cause parts to warp and even separate from the build tray. Both of these effects can contribute to an artefact's instability during printing, which can induce print failures. By orienting a artefact in the direction with the lowest aspect ratio, the relative material attached to the build tray is increased (stronger attachment to the tray), and the cumulative effect of residual stresses are reduced because fewer layers are needed.

5. Reduce weight and preserve stability by replacing solid volumes with cellular structures
With AM, the print time is much more sensitive to build height than geometry. Therefore, complex geometries such as cellular structures add little cost in manufacturing (they possibly even reduce cost). The implementation of cellular structures can reduce overall artefact weight while still preserving stability. Cellular structures, as opposed to solid structures, can also help to mitigate residual stresses in components (Fig. 3). The benefit of minimizing residual stresses is discussed in Principles 3 and 4 (Gibson, Rosen, et al., 2010).

Figure 3. A vase's structure is replaced with a Vornoi structure to provide the same functionality with less material (Principle 5)

6. Eliminate assembly steps and time by printing functional joints and interfaces directly
Artefacts with components that move relative to one another are traditionally assembled from different components manufactured separately because of the difficulty in removing material between the interfaces. With AM, since material is added rather than removed, such joints and interfaces can be printed directly as a single component. It is only necessary to ensure that the support material can be removed from the interface if there is any (Rosen, 2014).

7. Integrate additional functionality by incorporating components or features in unused internal volumes
The layer-by-layer nature of AM allows for access to the entire build volume of an artefact during manufacture, including its internal structure. Internal voids are accessible during the build process and

allow for components to be embedded and sealed with subsequently printed layers. Therefore, designers can use internal volumes to integrate additional functions (Fig. 4).

Figure 4. The aesthetic model is shelled and the top separated to provide storage functionality to the artefact (Principles 7 & 19)

8. Enable custom processes (i.e. low-medium volume production) by identifying features that are complex or require high levels of user-based customization
Certain products are difficult to manufacture traditionally because they require unique and complex geometries that are difficult to scale to volume production. AM's layer-by-layer process allows for the manufacture of complex geometries even when the geometries differ from part to part. In fact, a designer may take advantage of this characteristic to design artefacts with a wider range of variety, flexibility, and functionality (Keese et al., 2007).

9. Achieve desired mechanical properties by tailoring the geometry of the mesostructure
AM's selective placement of material allows the designer to tailor the mesostructure of components to provide the desired mechanical response. For instance, structural members can include voids or dimensional variation throughout its length resulting in a definable spring constant of the component (Fig. 5).

Figure 5. The profile of this clip is altered to provide a lower spring constant and be easier to use while the internal geometry remains the same (Principle 9)

10. Reduce print time by orienting the shortest dimension parallel to the slowest fabrication direction
With AM, print time is most sensitive to the direction in which the layers are stacked. An artefact may be oriented such that the shortest dimension is provided along this direction for reduced print times (Gibson, Rosen, et al., 2010).

11. Ensure printability by scaling artefacts and removing non-critical volumes
AM print volumes can be a limiting factor on part size. Another approach to ensure printability is to scale parts to be smaller or trim unnecessary volumes that may otherwise make the artefact too large for the built volume.

12. Improve accuracy of critical curves and profiles by orienting critical curves and profiles in the plane of highest resolution
Different AM technologies often will have different resolutions capabilities in different build planes. For instance FFF can produce curves with better detail in the plane perpendicular to the extrusion nozzle. Therefore, orienting critical curves and profiles in this perpendicular plane will yield a better result versus orienting them otherwise (Gibson, Goenka, et al., 2010).

13. Satisfy alternative functional requirements by scaling the artefact
The time required to digitally design an artefact is a significant portion of the AM design process; therefore components reuse can save a significant amount of time. Existing digital components may be repurposed to provide alternative functionality if scaled to be larger or smaller.

14. Satisfy different parametric requirements by scaling the artefact
As the time required to model an artefact is a significant portion of the entire AM design process, components reuse can save time. However there may not exist components that satisfy the parametric requirements of a design. It is shown that artefacts originally design to satisfy larger or smaller requirements can be scaled to better suit the requirements of the new artefact.

15. Minimize design time and effort by reusing already-designed component geometry
Component reuse may be used to minimize design time and cost. Analogously, already-designed digital artefact components and geometries can be reused to minimize or eliminate the time necessary to create the digital representation of the artefact (Fig. 6).

Figure 6. The thread geometry used to create one dremel attachment is reused to create another artefact for use with a dremel tool (Principle 15)

16. Leverage the capabilities of different AM technologies by using .STL files of sufficient resolution
The designer should ensure that the resolution of an artefact's digital representation (most commonly an .STL file) is of sufficient resolution for the selected AM technology.

17. Accommodate different AM technologies' capabilities by using high-resolution .STL files
Different AM processes may have different resolution capabilities. For an artefact that is to be printed using multiple technologies, high resolution meshes and .STL files can ensure that the resolution of the part file will leverage the full resolution capabilities of the selected AM process.

18. Improve printability by designing with the resolution limitations of the selected AM process in mind
Understanding the resolution capabilities of a selected AM process can be important for the designer when creating the digital representation of an artefact. Some processes may not produce thin walls or sharp corners very well because of technological limitations. Understanding these limitations is important when designing the artefact.

19. Add function(s) to artefacts by incorporating functional features into existing non-functional aesthetic models
Non-functional aesthetic models can be easily adapted and integrated with functional components to create products that have the appearance of the existing model, but with additional functionality. This is also demonstrated in Figure 4.

20. Minimize assembly time and number of components by incorporating snaps fits when possible
Designing snap fits directly into artefacts that need to be assembled can minimize assembly time and components (Boothroyd et al., 2010).

21. Reduce production time by standardizing the assembly process
When producing artefacts that need to be assembled from multiple, smaller, components, the assembly process should be standardized. This standardization can be done in multiple ways including, using similar connections or fastener types, using standard modules. Many of the same principles from Pahl and Beitz's design for assembly and manufacturing apply here (Boothroyd et al., 2010; Pahl et al., 2007).

22. Incorporate existing low-cost components by integrating the necessary standard interfaces
Off-the-shelf components are shown to reduce design time and cost. The designer should not neglect to consider these components when using AM. Interfaces for such components can be designed into an artefact and assembled post print. The quadcopter in Figure 7 shows a design modified to incorporate aluminium tubing. The tubing improves the design as it is cheap, readily available, and stiffer than the FFF material (Boothroyd et al., 2010).

Figure 7. This quadcopter design is modified to use aluminum struts instead of being fully additively manufactured (Principle 22)

23. Improve manufacturability by dividing artefact into smaller components
Build volume is often a limiting factor to artefact size when utilizing AM. Artefacts that are too large for a single build volume can be divided into smaller more appropriately sized subcomponents that can be manufactured in the selected build volume (Fig. 8).

Figure 8. This mask is split in to two pieces to accommodate a smaller build volume (Principle 23)

3.2 Principle Analysis

Building on the principles stated and defined in Section 3.1, other meta-information may be drawn from the extracted principles as a whole. Each of the 23 design principles is grouped by one of three improvement characteristics: quality, functionality, or printability. Quality refers to the mechanical qualities of the printed part (e.g. surface quality or strength), functionality refers to the functions or capabilities of the part, and printability refers to the likelihood of printing without build errors or failure. Of the 23 cumulative principles, 3principles consider improvement in quality, 9 seek to improve printability, and 11 seek to improve functionality as shown in Table 2.

Table 2. Breakdown of principles by improvement metric

Improvement	**Number**
Functionality	11
Printability	3
Quality	9

The extracted principles may also be resolved to different levels of specificity under design for manufacturing and assembly. While artefacts from Thingiverse are designed most typically for FFF processes, it is expected to find principles that relate to manufacturing in a more general sense. At the most specific level, there are principles that relate to FFF and more generally are principles for additive manufacturing. Beyond these abstraction levels are principles for digital manufacturing and most generally is design for manufacturing and assembly (DFMA) principles as shown in Figure 9.

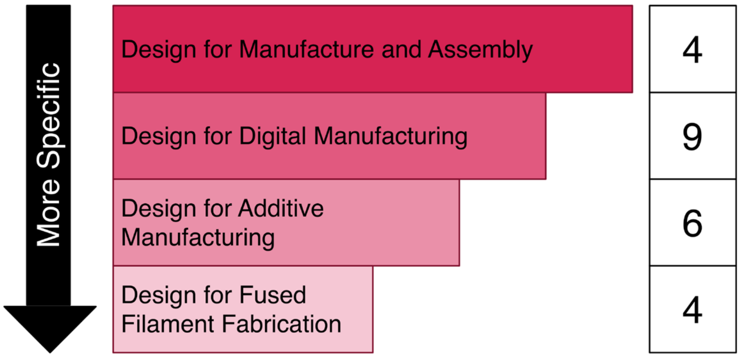

Figure 9. Hierarchy of principles under design for manufacturing and assembly

From Figure 9, four of the extracted principles are related to FFF specifically. For instance, *avoiding support material to preserve small features or surface finish* is especially important to FFF. With many single material capable FFF machines, support structures are often made of the build material and can interfere with small features or leave marks when removed. While this principle might apply to other AM processes, it does not apply to all (such as selective laser sintering which requires no support material). Eight of the extracted principles relate most specifically to DFAM. For example, *printing functional joints instead of assembling them* is a feature unique to AM and reduces the need for assembly or multiple components. Seven of the principles relate to digital manufacturing. As an example, *part files can be easily scaled for producing a similarly shaped object with a different function* as the fabrication relies on the digital model for direct digital reproduction. The other four principles acknowledge design for manufacturing and assembly. *Using snap fits to secure components* is also a well-known principle that aids in assembly and thereby a product or systems manufacture. These examples demonstrate the different levels of principle specificity shown in Figure 9.

A number of the 23 principles can be mapped directly to existing work. This mapping demonstrates confidence that the principles extracted are actually meaningful. In the literature each of the principles is dispersed throughout many different publications and projects. Here they are presented in a more unified format, with particular principles that have been discovered or first stated from this research. Principles relating to different levels of specificity under DFMA are most certainly found in analogous literature. Even still, within a level of specificity, it is difficult to find work that unifies all of the extracted principles, and places them in the context of additive manufacturing field and design prototyping or fabrication processes. The best example that illustrates this statement is at the level of DFMA where 5 of the 8 principles can be mapped to a specific chapter in *Additive Manufacturing Technologies* (Gibson, Rosen, et al., 2010). Apart from this work, principles at other levels of specificity are often scattered throughout the literature, or never explicitly identified. By extension, this process may be considered powerful when searching for design principles at different levels of specificity or in a field where said principles have not yet been consolidated or explicitly discovered (Gibson, Goenka, et al., 2010; Rosen, n.d.; Seepersad et al., 2013).

4 LIMITATIONS AND FUTURE WORK

Some principles presented through this work can be viewed as an amalgamation of many principles scattered throughout the existing literature. Others are presented as novel and never before discussed. The validity of these new principles is assumed as an extension of the existing principles revealed using the same method. It is understood that to fully validate these new principles and the crowd-based principle extraction method, a more rigorous and repeatable extraction routine should be developed.

Future work will investigate inter-rater reliability and principle saturation with respect to dataset size. Moreover studies of the efficacy of these principles when implemented will be performed.

5 DISCUSSION AND CLOSURE

The research work presented in this paper shows promise in the ability to leverage crowdsourced design data to extract useful design principles. 23 principles are extracted relating to manufacturing and assembly, digital manufacturing, additive manufacturing, and, most specifically, fused filament fabrication. Of the 23 principles, 14 are mapped to existing principles proposed by the literature. These provide extensional validation to the remaining 9 that are considered novel. With respect to the employed research method, future work is required to further formalize the method for improved repeatability. Moreover, the method should be generalized in order to leverage different design repositories that may differ in structure from Thingiverse. The proposed principles can be considered a valuable resource to aid designers who may be unfamiliar with additive manufacturing technology to create novel products that push the unexplored limited of the process. The discovered and formalized principles also provide a foundation by which design methods and techniques may be developed to assist designers and design teams for various phases of the design process, in the creation of new technologies and artefacts, and in the development of new market processes for addressing the grand challenges of society.

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