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DESIGN HEURISTICS FOR ADDITIVE MANUFACTURING

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Abstract

The potential benefits of additive manufacturing (AM) have been expounded upon by many in academic, industry, media, and policy circles. These potential benefits include functional integration, reduced complexity, increased robustness and increased performance. Many designers would like to take advantage of these benefits to improve their designs, but are at a loss as to how they can best incorporate AM. Existing DfAM methods are not tailored to generating the high-level concepts desired in the early stages of the design process and often require AM process-specific knowledge. Therefore, we propose to provide an AM process-independent method for transferring the high-level knowledge necessary for reasoning about functions and configurations to designers in the context of AM. The chosen method to accomplish this knowledge transfer is design heuristics for AM, which we derive from an analysis of 275 existing AM artifacts. Twenty-nine process-independent heuristics are derived, and the feasibility of the heuristics is verified with two DfAM case studies: a car door and a fighter pilot helmet to provide an initial proof of concept.

Keywords: Additive Manufacturing, Design for Additive Manufacturing (DfAM), Design methods, Early design phases, Design heuristics

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1 INTRODUCTION

The potential benefits of additive manufacturing (AM) have been expounded upon by many in academic, industry, media, and policy circles. These potential benefits include functional integration (e.g. GE Leap Engine fuel nozzle (Kellner, 2014)), reduced complexity (e.g. assembly part count reduction in washing rotor (EOS, 2016)), increased robustness (e.g. speed and temperature measurement probes for jet engines (EOS, 2015a)), and increased performance (e.g. conformal cooling in injection molds (EOS, 2015c)). A wide range of designers would like to take advantage of AM to improve their designs instead of just using AM to manufacture existing designs, but are at a loss as to how they can best incorporate it. Meeting this desire is complicated by the facts that neither novice nor experienced designers often have much experience utilizing AM and that the capabilities of AM are constantly advancing. Consequently, designers need design assistance for AM-enabled design, re-design, and production.

Many computational Design for Additive Manufacturing (DfAM) approaches are already available, which offer assistance in configuration and detailed design. However, these methods are not tailored to generating the high-level concepts desired in the early stages of the design process and often require AM process knowledge, which may unnecessarily limit the creative freedom of the design if a designer is not familiar with a wide range of processes. Therefore, we propose to provide an AM process-independent method for transferring the high-level knowledge necessary for reasoning about functions and architectures to both novice and expert designers; this method is design heuristics for AM.

The structure of the paper is as follows: background information on the chosen design method is found in Section 2, followed by a description of the heuristic derivation method and derived heuristics in Section 3. Two case studies verifying the feasibility of the heuristics are presented in Section 4, and the results are discussed in Section 5, followed by the limitations and future work. The paper concludes in Section 6.

The main contribution of this work is 29 AM-process independent design heuristics to aid designers in the early phases of the product development process.

2 BACKGROUND

Efforts to design for AM are hindered by previous knowledge of the constraints imposed by traditional manufacturing techniques, and an effort must be made to assist designers in breaking out of the traditional mindset (Seepersad, 2014). Subsequently, DfAM is currently a popular topic in academic and industry literature. Computational tools and design guidelines are among the most popular methods found in literature, although general DfAM processes can also be found. The computational tools mostly consist of shape and topology optimizers enabled by the near complete geometric freedom afforded by AM (see Rosen (2016) for a review of such methods), but this group of tools also includes tools specialized for certain tasks, such as determining optimal assembly points and minimizing the required support material, e.g. Yao et al. (2015). The shape and topology optimization methods require detailed knowledge of the material properties of the material to be utilized to achieve accurate, real-world results (Stanković et al., 2016), something which is difficult for many design teams to acquire, especially in the early stages of design.

While the computational tools seek to explore the geometric freedoms allowed by AM, the design guidelines seek to characterize the geometric limitations. They are typically a list of geometric constraints for a specific AM process, material, and, often, machine. They provide information about maximum overhang distances, minimum overhang angles, minimum feature thicknesses, minimum feature clearance, etc. They often also include design heuristics to assist in the removal of support material (e.g. addition of venting holes) and maintain high-part quality (e.g. part print orientation to prevent stepping). They sometimes focus on the design of certain feature types (e.g. bearings (Stöckli et al., 2016)). Examples of these abound in literature and industry. Urbanic and Hedrick (2016) and Adam and Zimmer (2014) are typical examples.

If one is following a structured design process (e.g. that of Ulrich and Eppinger (2008)), the previously discussed methods are not useful in the early, conceptual design steps, during which most of the pivotal design decisions are made, because they often require advanced process knowledge and/or a previously chosen conceptual idea. Unfortunately, methods to explore the AM design space during the conceptual design phase are still largely absent, although they are laid out as a specific need in the 2009 Roadmap for Additive Manufacturing (Bourell et al., 2014). Laverne et al. (2015) proposed offering designers informal information about AM processes and capabilities in the conceptual design phase, and they see promise in the general idea of providing AM-process information at that stage. Cognitive and design heuristics have proven themselves useful in a variety of situations as a way to quickly and easily communicate synthesized knowledge typically gained through long experience to those new to a task (Fu et al., 2016), a notable example of which are the cognitive design heuristics developed by Yilmaz and Seifert (2010). As a way to quickly transfer knowledge of AM capabilities to designers, design heuristics are a promising choice, given their track record. Therefore, we propose to develop a list of AM process-independent, design heuristics for AM.

3 METHOD

A heuristic is defined as "a context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution (Fu et al., 2016)." A knowledge base is an essential ingredient in the derivation of heuristics. Because of the ever-expanding design pool realized through AM, it would be short-sighted to limit the knowledge base of the AM design heuristics to personal knowledge, personal experience, or existing design principles. Therefore, the chosen method for deriving the heuristics is the analysis of existing designs, which is also the most common method among design principle, guideline, and heuristic derivation research (Fu et al., 2016).

Figure 1. Method Diagram

Our specific approach is similar to that of Yilmaz and Seifert (2010) and is described in Figure 1. First, we collect the sample pool of AM artifacts and then analyze the key functions and features of each sample pool artifact. Next, these collected functions and features are mined to determine possible AM design heuristics. Then, the list of heuristics is compiled, during which similar heuristics are combined and generalized to ensure process-independence. Finally, the feasibility of the heuristics is verified using two case studies.

Our method mainly differs from that of Yilmaz and Seifert (2010) in that our pool-inclusion criteria is different. Our inclusion criteria are the following:

1. The artifact must be primarily manufactured using AM.
2. The production of relevant design feature(s) must be either solely possible with AM or greatly eased by it.

There are no criteria for including only "good" designs in the heuristics derivation, like Yilmaz and Seifert (2010), because, to our knowledge, there is no existing list classifying what "good" AM designs are. Additionally, there are no constraints considering the number of times a heuristic must or should appear within the sample pool to be included in the final list. This is because of the constant innovation in the application of AM; it would be a shame to exclude an innovative heuristic from the list on the basis of too few extant occurrences. Along the same lines, we do not indicate the number of occurrences of each heuristic within our sample, with the goal of avoiding the display of preference or superiority of one heuristic over another. Finally, there are no restrictions concerning the usability, practical application, or completeness of the artifact, i.e. innovative metamaterials, artifacts consisting of AM and non-AM parts, and a portion of an artifact are all equally eligible. This allowance is again due to the ever-expanding capabilities of AM, which sometimes advance by baby-steps rather than by leaps and bounds.

A variety of sources contribute to the list of examined artifacts. We draw artifacts from academic and industry literature, as well as the popular media. Industry websites of AM machine producers and the hobby website Thingiverse (Thingiverse, 2016) are also consulted. Our list of artifacts is by no means exhaustive, but we believe it provides a good cross-section of the state of the art of AM artifacts.

Two-hundred and seventy-five artifacts are examined following our method to derive the list of 29 design heuristics for AM found below in Table 1. Following the recommendation of Fu et al. (2016), they are formulated in the declarative form. Each heuristic is accompanied by an example from the pool of examined artifacts.

Some of the heuristics that may be less straight-forward are also further elaborated upon, namely, *Consolidate parts to achieve multiple functions* (#4), *Use metamaterial to achieve desired material properties* (#15), and *Use material distribution to achieve desired behavior* (#19).

Table 1. List of derived Design Heuristics for AM accompanied by examples (continued on the next page)

Heuristic ID Number	Heuristic	Example
1	Consolidate parts for better functional performance	GE Leap Engine fuel nozzle (Kellner, 2014)
2	Consolidate parts to reduce assembly time	Part count reduction in washing rotors (EOS, 2016)
3	Consolidate parts to increase robustness	Speed and temperature measurement probes for jet engines (EOS, 2015a)
4	Consolidate parts to achieve multiple functions	Injection mold conformal cooling channels (EOS, 2015c)
5	Customize geometry to use case	Handheld sandblaster housing (Materialise, 2016)
6	Customize user interface to use case	Motorcycle helmet with custom inlay (Jones et al., 2009)
7	Customize artifact with decoration	3D Printed Tote Bag with Monkey Pattern (Materialise, 2014)
8	Convey information with color	Eye prostheses (American Academy of Ophthalmology, 2014)
9	Convey information with geometry	Sign with raised letters (Keating and Oxman, 2013)
10	Convey information with haptics	Surgical prep models offer realistic tissue response (Stratasys, 2013)
11	Convey information with light	Postcard image visible when held up to the light (Vidimče et al., 2013)
12	Use biocompatible material	Cranial implant (EOS, 2015b)
13	Use biodegradable material	Biodegradable tracheal implant (EOS, 2013)
14	Use metamaterial to achieve recyclability	Single material car door handle (Hopkinson et al., 2006)
15	Use metamaterial to achieve desired material properties	Auxetic metamaterial (Schwerdtfeger et al., 2011)
16	Use variable metamaterial to achieve variable material properties	Flip-flop sole (Bickel et al., 2010)
17	Use multiple materials to achieve functionality	Variable impedance prosthetic socket (Sengeh and Herr, 2013)
18	Use multiple materials to achieve variable material properties	Multi-material lattice structure (Stankovic et al., 2015)
19	Use material distribution to achieve desired behavior	Thin-walled air-pocket in prosthetic socket (Montgomery et al., 2009)
20	Embed functional material	Soft-material hinges in bistable actuator (Chen et al., 2016)
21	Embed functional component	Accelerometer in helmet insert (Castillo et al., 2009)
22	Use enclosed, functional parts	Single print ball and socket joints (Calì et al., 2012)

Heuristic ID Number	Heuristic	Example
23	Replace internal structure with lightweight cellular/lattice structure	Unmanned aerial vehicle wing (Namasivayam and Seepersad, 2011)
24	Hollow out artifact to reduce weight	Nearly hollow airfoil (Ponche et al., 2014)
25	Absorb energy with small interconnected parts	Elastic energy storage (Raney et al., 2016)
26	Allow movement with small interconnected parts	Scale-based armor (Johnson et al., 2013)
27	Remove material to provide function	Ventilation holes in wrist splint (Paterson et al., 2015)
28	Optimize structural topology or geometry	Water manifold redesign to reduce vibration (Loncke, 2014)
29	Create multi-functional artifact with reconfigurable structures	Hierarchical multi-stable structures (Chen and Shea, 2016)

Consolidate parts to achieve multiple functions (#4) refers to part consolidation with the purpose of increasing the number of functions performed by a part. For example, an injection mold with conformal cooling channels performs the functions of both forming and cooling the plastic. Other examples include air and fluid channels that can direct flows, heat or cool the artifact, or enable actuation, which are embedded into a structural part. Maintenance access, wire routing channels, and movement guides are also possibilities.

Use metamaterial to achieve desired material properties (#15) refers to, often exotic or special, material properties achieved by varying the microstructure of the material, usually only realizable through the use of AM. An abbreviated list of examples from the artifact pool of metamaterials achieved with AM include specific mechanical responses, controlled thermal expansion, specific porosity, extreme anisotropy, acoustic dampening, control of bone/cell growth, artificial magnetism, and electromagnetic stealth behavior.

Use material distribution to achieve desired behavior (#19) refers to the macro-level distribution of material to achieve a function or desired behavior. Example applications include the integration of a spring-shaped geometric appendage or barrel-pin hinge directly into the artifact geometry instead of adding a separate spring or hinge during post-production. Bendable hoses for flexibility and thin-walled cavities for air-pressure controlled actuation are also covered by this heuristic.

4 RESULTS

Below are two case studies that verify the feasibility of these design heuristics: a multi-material fighter pilot helmet and a car door manufactured from a single material. The case studies are selected since they are both multi-functional products that could be fabricated in part or in full by AM, either now or in the future. Similar, simpler versions of these case studies are already under development including several impact absorbing 3D printed materials and structures developed as part of the Head Health Challenge fabricated using AM (Head Health Challenges, 2015) and AM manufacture of large-scale functional artifacts (Walker, 2016, Eichenhofer et al., 2015). The case studies are performed by the first author and are original designs to illustrate the heuristics, i.e. they are not based on other case studies or specific existing artifacts.

4.1 Case Study: Fighter Pilot Helmet

The demands on the design of a fighter pilot helmet are many. Its primary function is to protect against impacts, but it must also serve as a mounting point for life-support, communication, and eye-protection devices while at the same time being comfortable for the pilot to wear for extended periods. Figure 2 illustrates the application of the design heuristics for AM to the design of a fighter pilot helmet with the goal of meeting these demands. Callouts indicate different points of interest in the design. The design is described below.

The helmet is fabricated in one piece (#2 *Consolidate parts to reduce assembly time*), which has the added advantage of making the integrated air channels (for oxygen and cooling purposes) hermetically sealed (#1 *Consolidate parts for better functional performance*, #4 *Consolidate parts to achieve multiple functions*). The material distribution of the external air hose allows for flexibility (#19 *Use material distribution to achieve desired behavior*). Multi-material bands in the air mask allow the helmet and air-mask to be slipped over the head in one piece and the chin-strap has a multi-material cushion (#17 *Use multiple materials to achieve functionality*, #18 *Use multiple materials to achieve variable material properties*) and an integrated snap-fit clasp (#4 *Consolidate parts to achieve multiple functions*). The geometry of the entire helmet can be personalized to fit the pilot, from the size to the internal curvature of the padding to the face-mask geometry (#6 *Customize user interface to use case*), and the shell can be optimized for defined load cases (#5 *Customize geometry to use case*, #28 *Optimize structural topology or geometry*). Embedded wiring allows for radio, heads-up display, and headphone connections (#20 *Embed functional material*), and a locator antenna is embedded into the shell (#21 *Embed functional component*). The cushioning is a functionally-varied metamaterial, which optimally provides cushioning and acoustic dampening, as necessary (#5 *Customize geometry to use case*, #15 *Use metamaterial to achieve desired material properties*, #16 *Use variable metamaterial to achieve variable material properties*, #28 *Optimize structural topology or geometry*). The sun visor moves in and out with the help of integrated multi-stable structures (#29 *Create multi-functional artifact with reconfigurable structures*), the guide-track for the eye-shield is integrated into the helmet geometry, and there are integrated mounting points for the heads-up display system (#4 *Consolidate parts to achieve multiple functions*). Finally, the helmet is easily decorated to display a logo or pilot call sign (#7 *Customize artifact with decoration*, #8 *Convey information with color*).

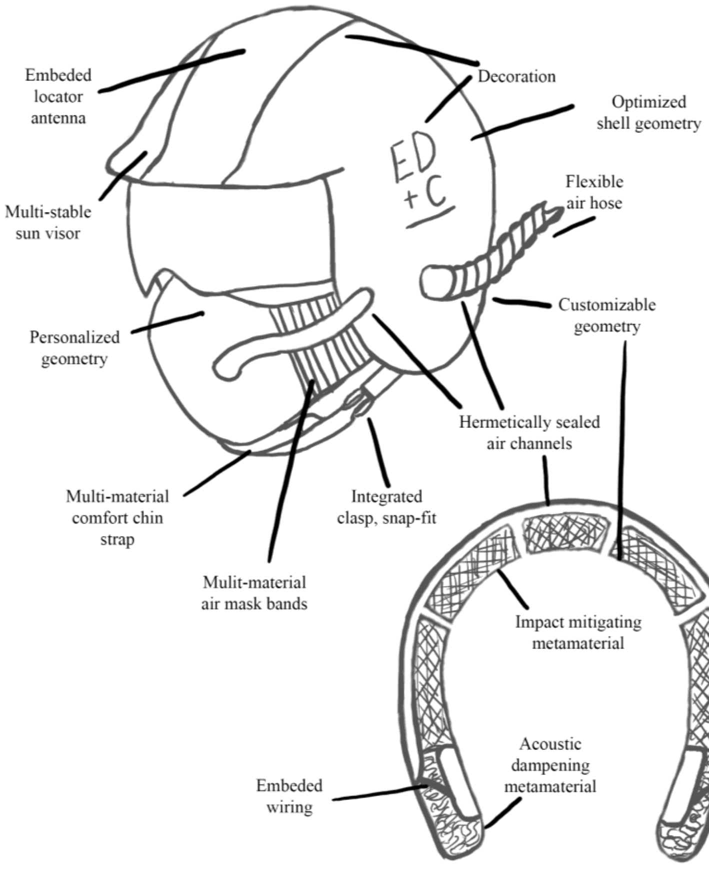

Figure 2. Illustration of Fighter Pilot Helmet Case Study

4.2 Case Study: Car Door

The primary functions of a car door include closing-off the passenger cabin from the external environment, protecting the passengers from external forces (e.g. weather, crash-impacts), and allowing access to the cabin. However, as fuel efficiency demands lead to the demand for lighter cars and cars have become lifestyle products attention must also be paid to lightweight and customized constructions. Figure 3 illustrates the application of the design heuristics for AM with the goal of designing a car door. Callouts indicate different points of interest in the design. The design is described below.

The door is fabricated in one piece and in a single material, which provides the dual benefit of recyclability (#14 *Use metamaterial to achieve recyclability*) and resistance to dislodgement from vibrations (#3 *Consolidate parts to increase robustness*). The space frame topology of the door is optimized to reduce the overall weight and meet crash requirements (#28 *Optimize structural topology or geometry*), it may however be easily modified to meet stricter requirements (e.g. police vehicle) (#5 *Customize geometry to use case*). The internal structure of the door is a graded metamaterial which is stiff and light at the external interface, but also facilitates energy absorption in the internal panels to avoid the use of foams and glues (#15 *Use metamaterial to achieve desired material properties*, #16 *Use variable metamaterial to achieve variable material properties*, #23 *Replace internal structure with lightweight cellular/lattice structure*) and allows total freedom to add decorative elements at the surface, which are easily varied from customer to customer (#6 *Customize user interface to use case*, #7 *Customize artifact with decoration*). The door lock, handle, mirror hinge, and window mechanism either are embedded into the door (#21 *Embed functional component*) or are integrated into the door to make non-assembly mechanisms (#2 *Consolidate parts to reduce assembly time*, #22 *Use enclosed, functional parts*). Wiring and maintenance channels are embedded into the cellular geometry to guide wires for speakers, window controls, and door locks, and fastening points for an interior cloth covering and the door hinge are integrated into the artifact (#4 *Consolidate parts to achieve multiple functions*). Finally, maintenance points are indicated by raised geometric indicators (#9 *Convey information with geometry*).

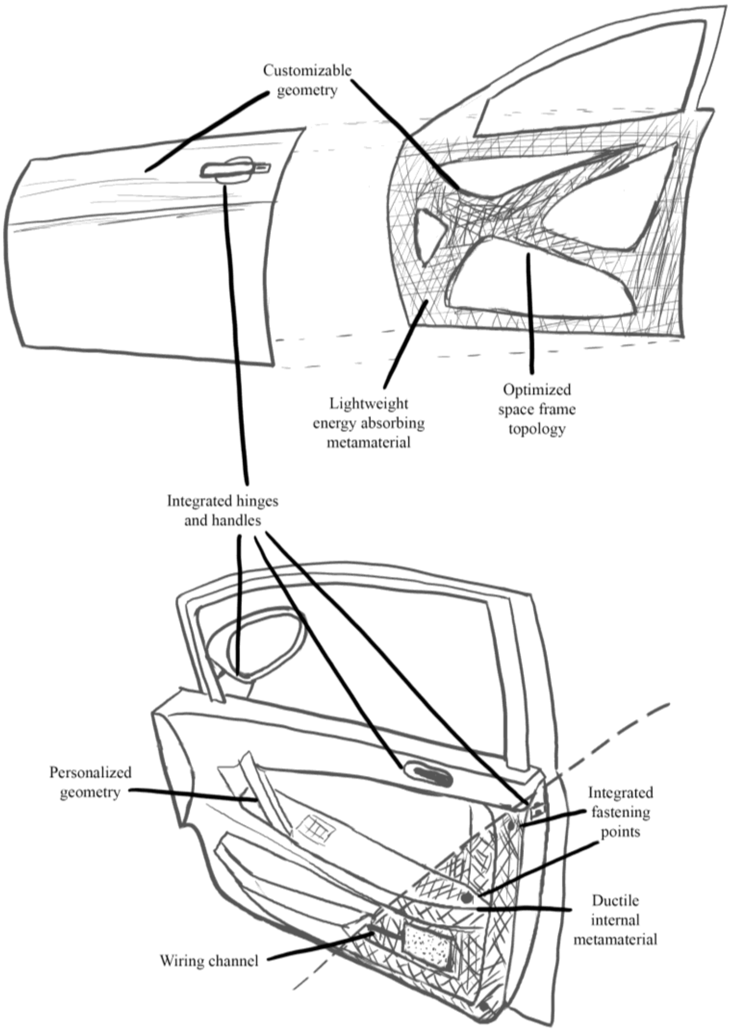

Figure 3. Illustration of Car Door Case Study

5 DISCUSSION

In comparison to the context-dependent heuristics derived by Yilmaz and Seifert (2010) and the context-independent heuristics found in TRIZ, Synetics, and SCAMPER, the wording of the proposed heuristics falls somewhere in-between. The heuristics we derive could be more specific (e.g. *Use metamaterial to* *achieve desired material properties* could be broken down into *Use metamaterial to achieve desired mechanical properties*, *Use metamaterial to achieve desired thermal properties*, *Use metamaterial to achieve desired acoustic properties*, etc.), but we do not want a list that would explode in length and require frequent revisions as AM applications and technology advances.

Very specific heuristics would also be counterproductive to our goal of keeping the heuristics as process- and material-independent as possible. We do not reference any particular processes or materials in the text and try to steer away from implying any connection. For example, if thermal material properties are mentioned, due to the paradigm knowledge of traditional design and manufacturing, the designers' thoughts may immediately direct themselves toward insulating foams or conductive metals, which may not be the best solution for achieving the desired properties when enabled by AM. We also avoid the reference of specific materials when referencing recyclability, biocompatibility, and biodegradability in the heuristics as new materials may fit these categories in the future. Finally, although those with AM process-knowledge may immediately jump to specific materials and processes when they read *multiple materials*, these assumptions are based on the current state of the art in AM, and further specifying which materials to combine would date and limit the validity of the heuristics.

We avoid the inclusions of general design heuristics to retain the focus on AM, although some heuristics could be interpreted generally as well. This is, however, not the goal. In actual practice, we anticipate that these design heuristics for AM will act as a supplement to other, general design heuristics and that DfAM will be naturally incorporated into the traditional design process.

Two case studies are performed to verify the feasibility of the AM design heuristics and provide a proof-of-concept. In the case of the helmet, 16 unique heuristics are applied, and in the case of the car door, 14 unique heuristics are applied. Between the two case studies, 21 of 29 heuristics are utilized. A usage rate this high over two case studies is considered a success for the initial verification. Additionally, new functions (e.g. venting, wire-direction channels) are added to both artifacts, and the previously existing functions are now realized in a way that is impossible, too expensive, or tedious without AM (e.g. lightweight structural support, customized helmet geometry, customized decoration).

The case studies consider designs that can today, in part, be fabricated with AM and could in the future be fabricated in full with AM through upcoming technological advancement. This illustrates the point that the design heuristics aim to avoid a high-level of detail or connection to specific processes and are thus aimed at the conceptual level that is process and material independent. In our case studies, the heuristics are applied to the entire artifact or large subassemblies; however, this need not be the case. If one finds that AM of an entire artifact (e.g. a helmet) is infeasible or cost prohibitive, these heuristics can still be applied to portions of the artifact (e.g. custom fit internal helmet cushioning system), which could be realized using AM today. The design heuristics are intended to attain longevity in such a fast changing technological domain so that they are useful today and in the foreseeable future.

Besides the lack of validation from a user study and the relative subjectivity of the derivation method, there are some other limitations to this work. First, the rapidly expanding pool of knowledge and applications with regards to AM could shortly render the comprehensiveness of the heuristics deficient, despite efforts to make the heuristics general enough to encompass further innovations. Secondly, these heuristics are representative of what is currently possible with AM, not necessarily the best practices with regards to DfAM, which are still being defined at a conceptual level by the design community. Finally, there is some crossover in applicability between heuristics (e.g. customizing the internal cushioning in the helmet may be achieved through heuristic #5 *Customize geometry to use case* or #6 *Customize user interface to use case*), which could make using the heuristics somewhat ambiguous for designers, especially those who are inexperienced.

5.1 Future Work

This work analyzes 275 AM case studies to derive 29 design heuristics for AM and verifies the feasibility of the use of these heuristics as a DfAM method with two case studies. Future user studies with both novice and expert designers need to be conducted in order to explore the applicability of the method.

6 CONCLUSION

In this work, we address the challenge of providing a process-independent and high-level DfAM method for the early stages of the product development process. We perform an analysis of existing AM artifacts to develop a list of design heuristics for AM. We verify their feasibility with two case studies. Their usefulness in actual design scenarios will be validated with future user studies.

REFERENCES

Adam, G. A. O. and Zimmer, D. (2014), Design for Additive Manufacturing—Element transitions and aggregated structures. *CIRP Journal of Manufacturing Science and Technology*, 7, 20-28. http://dx.doi.org/10.1016/j.cirpj.2013.10.001

American Academy of Ophthalmology (2014), *3-D Printed Facial Prosthesis Offers New Hope for Eye Cancer Patients Following Surgery*, Chicago, Illinois, USA: American Academy of Ophthalmology.

Bickel, B., Bächer, M., Otaduy, M. A., Lee, H. R., Pfister, H., Gross, M. and Matusik, W. (2010), “Design and fabrication of materials with desired deformation behavior”, *ACM Transactions on Graphics*, 29, 1. http://dx.doi.org/10.1145/1778765.1778800

Bourell, D. L., Rosen, D. W. and Leu, M. C. (2014), “The Roadmap for Additive Manufacturing and Its Impact”, *3D Printing and Additive Manufacturing*, 1, 6-9. http://dx.doi.org/10.1089/3dp.2013.0002

Calì, J., Calian, D. A., Amati, C., Kleinberger, R., Steed, A., Kautz, J. and Weyrich, T. (2012), “3D-printing of non-assembly, articulated models”, *ACM Transactions on Graphics*, 31, 1. http://dx.doi.org/10.1145/2366145.2366149

Castillo, S., Muse, D., Medina, F., Macdonald, E. and Wicker, R. (2009), “Electronics Integration in Conformal Substrates Fabricated with Additive Layered Manufacturing”, *Solid Freeform Fabrication Symposium 2009*. Austin, Texas, USA.

Chen, T., Mueller, J. & Shea, K. (2016), “Design and Fabrication of a Bistable Unit Actuator with Multi-Material Additive Manufacturing”, *Solid Freeform Fabrication Symposium 2016*. Austin, Texas, USA.

Chen, T. and Shea, K. (2016), “Design and Fabrication of Hierarchical Multi-Stable Structures Through Multi-Material Additive Manufacturing”, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2016*. Charlotte, NC, USA: ASME.

Eichenhofer, M., Maldonado, J. I., Klunker, F. & Ermanni, P. (2015), “Analysis of Processing Conditions for a Novel 3D-Compositre Production Technique”, *20th International Conference on Composite Materials*. Copenhagen, Denmark.

EOS. (2013), Medical: *University of Michigan - Customizing a biocompatible material for additively manufactured medical implants* [Online]. eos.info: EOS. Available: https://www.eos.info/press/customer_case_studies/University-of-michigan-biocompatible-material-for-additive-manufacturing (Accessed 29 November 2016).

EOS. (2015a), Aerospace: *Vectorflow - Additive Manufacturing of probes for measuring speed and temperature in turbo engines* [Online]. eos.info. Available: https://www.eos.info/aerospace-vectoflow-additive-manufacturing-of-probes-for-measuring-speed-and-temperature-in-turbo-engines-ea0691d8a20ee1eb (Accessed 29 November 2016).

EOS. (2015b), *Improved Quality of Life Thanks to Cranial Implants Produced with Additive Manufacturing* [Online]. Available: https://scrivito-public-cdn.s3-eu-west-1.amazonaws.com/eos/public/1d0369c9fdb43f6a/b89eccf1571d0c7004f4a55b9e660bb5/download_Case_Study_alphaform_canial_implant.pdf (Accessed 29 November 2016).

EOS. (2015c), *Industrial 3D printing for Tooling - Function integration, faster amortisation* [Online]. eos.info. Available: https://www.eos.info/tooling (Accessed 29 November 2016).

EOS. (2016), *Functional Integration* [Online]. eos.info. Available: https://www.eos.info/additive_manufacturing/for_your_technical_innovation/challenge_functional_integration (Accessed 29 November 2016).

Fu, K. K., Yang, M. C. and Wood, K. L. (2016), “Design Principles: Literature Review, Analysis, and Future Directions”, *Journal of Mechanical Design*, 138, 13. http://dx.doi.org/10.1115/1.4034105

Head Health Challenges. (2015), *Challenge III Winners* [Online]. ninesigma.com: Head Health Challenges. Available: https://ninesights.ninesigma.com/web/head-health/challenge-3-winners (Accessed 13 April 2017).

Hopkinson, N., Gao, Y. & McAfee, D. J. (2006), “Design for environment analyses applied to rapid manufacturing”, *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 220, 1363-1372. http://dx.doi.org/10.1243/09544070jauto309

Johnson, A., Bingham, G. A. and Wimpenny, D. I. (2013), “Additive manufactured textiles for high-performance stab resistant applications”, *Rapid Prototyping Journal*, 19, 199-207.

Jones, J., Jones, C. L. and Wimpenny, D. I. (2009), “Customised Rapid Manufactured Parts: Technology and Case Studies from the Custom-Fit Project”, *Solid Freeform Fabrication Symposium 2009*. Austin, Texas, USA. http://dx.doi.org/10.1108/13552541311312193

Keating, S. and Oxman, N. (2013), “Compound fabrication: A multi-functional robotic platform for digital design and fabrication”, *Robotics and Computer-Integrated Manufacturing*, 29, 439-448. http://dx.doi.org/10.1016/j.rcim.2013.05.001

Kellner, T. (2014), *Fit To Print: New Plant Will Assemble World's First Passenger Jet Engine With 3D Printed Fuel Nozzles, Next-Gen Materials* [Online]. GEReports.com. Available: http://www.gereports.com/post/80701924024/fit-to-print [Accessed 29 November 2016].

Laverne, F., Segonds, F., Anwer, N. and Le Coq, M. (2015), “Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study”, *Journal of Mechanical Design*, 137, 121701. http://dx.doi.org/10.1115/1.4031589

Loncke, D. (2014), “Following Moore's Law”, *Mikroniek*, 54, 17-22.

Materialise. (2014), *Kipling: No Monkey Business* [Online]. Materialise.com. Available: http://www.materialise.com/cases/kipling-no-monkey-business (Accessed 29 November 2016).

Materialise. (2016), *Pinovo and Materialise* [Online]. Materialise.com: Materialise. Available: http://manufacturing.materialise.com/cases/pinovo-and-materialise-0 (Accessed 29 November 2016).

Montgomery, J., Vaughan, M. and Crawford, R. (2009), “Investigation and Design of an Actively Actuated Lower-Leg Prosthetic Socket”, *Solid Freeform Fabrication Symposium 2009*. Austin, Texas.

Namasivayam, U. M. and Seepersad, C. C. (2011), “Topology design and freeform fabrication of deployable structures with lattice skins”, *Rapid Prototyping Journal*, 17, 5-16. http://dx.doi.org/10.1108/13552541111098581

Paterson, A. M., Bibb, R., Campbell, R. I. and Bingham, G. (2015), “Comparing additive manufacturing technologies for customised wrist splints”, *Rapid Prototyping Journal*, 21, 230-243. http://dx.doi.org/10.1108/rpj-10-2013-0099

Ponche, R., Kerbrat, O., Mognol, P. and Hascoet, J.-Y. (2014), “A novel methodology of design for Additive Manufacturing applied to Additive Laser Manufacturing process”, *Robotics and Computer-Integrated Manufacturing*, 30, 389-398. http://dx.doi.org/10.1016/j.rcim.2013.12.001

Raney, J. R., Nadkarni, N., Daraio, C., Kochmann, D. M., Lewis, J. A. and Bertoldi, K. (2016), “Stable propagation of mechanical signals in soft media using stored elastic energy”, *Proceedings of the National Academy of Sciences USA*, 113, 9722-7. http://dx.doi.org/10.1073/pnas.1604838113

Rosen, D. W. (2016), “A review of synthesis methods for additive manufacturing”, *Virtual and Physical Prototyping*, 1-13. http://dx.doi.org/10.1080/17452759.2016.1240208

Schwerdtfeger, J., Wein, F., Leugering, G., Singer, R. F., Korner, C., Stingl, M. and Schury, F. (2011), “Design of Auxetic Structures via Mathematical Optimization”, *Advanced Materials*, 23, 2650-4. http://dx.doi.org/10.1002/adma.201004090

Seepersad, C. C. (2014), “Challenges and Opportunities in Design for Additive Manufacturing”, *3D Printing and Additive Manufacturing*, 1, 10-13. http://dx.doi.org/10.1089/3dp.2013.0006

Sengeh, D. M. and Herr, H. (2013), “A Variable-Impedance Prosthetic Socket for a Transtibial Amputee Designed from Magnetic Resonance Imaging Data”, *Journal of Prosthetics and Orthotics*, 25, 129-137. http://dx.doi.org/10.1097/JPO.0b013e31829be19c

Stankovic, T., Mueller, J., Egan, P. & Shea, K. (2015), “A Generalized Optimality Criteria Method for Optimization of Additively Manufactured Multimaterial Lattice Structures”, *Journal of Mechanical Design*, 137, 111405. http://dx.doi.org/10.1097/10.1115/1.4030995

Stanković, T., Mueller, J. & Shea, K. (2016), “Optimization for Anisotropy in Additively Manufactured Lattice Structures”, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2016*. Charlotte, NC, USA: ASME. http://dx.doi.org/10.1115/detc2016-59494

Stöckli, F., Modica, F. & Shea, K. (2016), “Designing passive dynamic walking robots for additive manufacture”, *Rapid Prototyping Journal*, 22, 842-847. http://dx.doi.org/10.1108/RPJ-11-2015-0170

Stratasys. (2013), *Flesh and Bone* [online]. Stratasys.com: Stratasys. Available: http://usglobalimages.stratasys.com/main/files/case%20studies/medical/polyjet-cs-cbmti-11-13.pdf?v=635280183584345551 (Accessed November 29 2016).

Thingiverse. (2016), *Thingiverse* [Online]. Available: http://www.thingiverse.com/ (Accessed 29 November 2016).

Ulrich, K. T. and Eppinger, S. D. (2008), *Product Design and Development*, Boston, Massachusetts, USA, McGraw Hill.

Urbanic, R. J. and Hedrick, R. (2016), “Fused Deposition Modeling Design Rules for Building Large, Complex Components”, *Computer-Aided Design and Applications*, 13, 348-368. http://dx.doi.org/10.1080/16864360.2015.1114393

Vidimče, K., Wang, S.-P., Ragan-Kelley, J. and Matusik, W. (2013), “OpenFab”, *ACM Transactions on Graphics*, 32, 1. http://dx.doi.org/10.1145/2461912.2461993

Walker, D. (2016), “Local Motors wants to 3D-print your next car out of plastic” [Online]. Wired.co.uk: Wired. Available: http://www.wired.co.uk/article/3d-printed-cars-local-motors-lm3d (Accessed 20 April 2016).

Yao, M., Chen, Z., Luo, L., Wang, R. and Wang, H. (2015), “Level-set-based partitioning and packing optimization of a printable model”, *ACM Transactions on Graphics*, 34, 1-11. http://dx.doi.org/10.1145/2816795.2818064

Yilmaz, S. and Seifert, C. M. (2010), “Cognitive Heuristics in Design Ideation”, *International Engineering Design Conference - Design 2010*. Dubrovnik, Croatia: The Design Society.