Improving the Education of DfAM

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I. Introduction and Motivation

Additive manufacturing (AM) has come a long way. Fast forward to the 2000s, the spread of 3-D printing is becoming more serious. Most printers use a computer-aided design (CAD) structure, which is then sent to a slicer that generates a G-Code file specific to the machine (which then prints the object). Various printing methods have been developed, with different characteristics or strengths. This point helps show the diversity in applicability that AM has. With its rising popularity, 3-D printing has become more accessible, allowing scientists and researchers for more hands-on experiments (thus improving the field). When compared to Traditional manufacturing (TM), where would AM stand? The advantages of AM over TM (also see Figure 1):

- Industrial efficiency: Consumers can build their CAD model and send it for manufacturing. Additionally, it could play an important role with on-demand manufacturing, where needed parts would be printed instantly rather than waiting for shipping.
- The complexity of structures: can print parts that no TM expert could do (inner cavities...).
- Sustainability: with additive, waste material is minimal (compared to subtractive).
- Rapid manufacturing: quick and inexpensive production compared to TM.

This list could expand a lot more, but this is only to show the potential of AM [1].

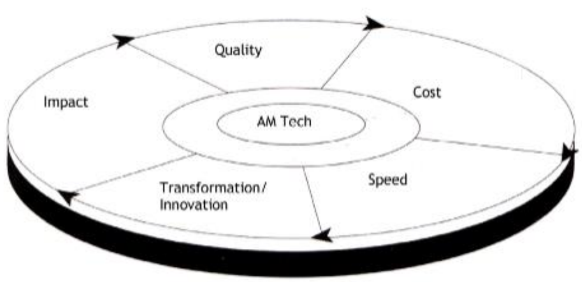


Fig. 1. *Five key benefits of AM over TM [1]*

Because of their fast and inexpensive printing cycles, 3-D printers were solely used for mockups (first phase). Those prototypes were modified with ease, allowing quick feedback from the customer and faster iteration cycles. Furthermore, companies would save a lot of money, and in-house production would allow more privacy. When the second phase (also called rapid prototyping) kicked in, AM was trying to produce finished goods. In the third and final phase, consumers owned 3-D printers. This allows non-scientists/researchers to print whatever they need (as long as it fits through the scope of the printer) [2].

As for the future of DfAM, it is still in the early stages of growth. It is still considered an emerging field, and TM is still available in many companies. Most people only see this field as a hobby for homemade DIY projects. The lack of ready-for-market 3-D printing products is still high. Creating complex geometries is possible, but there is a lack of design tools to do it. There is still room for a lot of expansion; the goal is to replace subtractive manufacturing (lathes, mills, drilling machines...), and be cheaper, faster, and more sustainable [3].

Following this AM spread, specific guidelines for new users still lack. Most guidelines follow specific assumptions (experienced user, distinct AM process, repeated information). Many solutions have also been discussed and published trying to solve this issue. With AM's growing popularity, a wide span of people, ranging from middle-school students to senior engineers, are showing interest in 3D printing. Both academia and industry need generalized guidelines [4].

Incorporating Design for AM (DfAM) requires knowledge and experience. With that said, the only open-source tools available to evaluate if a design is to be manufactured with AM (Can it be printed? Should it be printed) are not relatively simple to navigate. The purpose of this research is to create a tool that could provide help and guidance to people ranging from amateurs to professionals. Standard guidelines retrieved from various sources can help build a solid base for this tool. With this option, the percentage of successful prints should increase drastically.

II. Background

The strategy proposed to proceed with this research (to develop the idea mentioned in the Introduction) is based on the review of relevant literature that explains the implication related to DfAM and helps understand the necessary information. Also, this strategy finds means to evaluate the outcome of the design process. Furthermore, it locates and reviews guidelines that are used to evaluate DfAM designs (validation of the outcomes of the design process). Finally, it investigates how these tools perform, to generate a new and improved approach. The upcoming section will display the most relevant research done in this field (along with all key takeaways).

III. Litterature Review

Additive Manufacturing is a rapidly growing sector in design, prototyping, and manufacturing. It is crucial to provide a holistic approach that aims towards educating for the correct design methods and overviews of AM. While hardware and software become increasingly more accessible, design knowledge in this area lags due to a lack of comprehensive and uniform design tools.

Emerging design tools provide very narrow scopes and focus on the opportunistic side of AM rather than considering the restrictive side.

The Design for Additive Manufacturing Worksheet [4]

In this project, Booth et al. [4] focus on creating a tool to analyze the likelihood of a print success for a specific part using an intuitive worksheet. It enables users to identify key DfAM concepts prior to their final design, catering towards the novice and educational side of DfAM. While the paper explicitly asks: “can you print this with AM?”, it lacks the crucial question: “should you print this with AM?” (relating to opportunistic vs. restrictive). Identifying when AM is to be used (rather than TM) is essential. Additionally, the paper lacks an in-depth approach to all DfAM guidelines and only covers the surface.

To conduct this investigation Booth et al. [4] collaborated with Boilermaker Lab at Purdue, looking for common errors designers commonly do. Generated feedback helped create the worksheet's principal guidelines. Additionally, the authors reached out to experts and 3-D printing labs. It aided the team in enhancing the tool and fixing common mistakes.

The authors verified the tool's effectiveness by testing parameters (such as tracking the number of failed prints and in-class testing for learning outcomes). Finally, the worksheet showed a significantly reduced number of failed prints or reprints for both study groups.

Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study [5]

The paper proposes a novel overview of all existing DfAM methods. Additionally, it introduces a new classification for these methods (opportunistic vs. restrictive):

- Opportunistic DfAM encourages designers (or students) to explore/experiment/educate themselves on the potentials of AM (complex geometries, traditionally impossible to produce parts, multi-materials, etc.)
- Restrictive DfAM encourages designers (or students) to consider the limitations of AM (usable materials and their properties, bridging, minimum feature size, etc.)
- Dual DfAM attempts to join both classifications to consider all sides of AM.

The paper also identifies two others existing DfAM methods: C-DfAM (component-level) and A-DfAM (assembly-level). It proposes a new approach (eA-DfAM), which suggests a structured approach in the early design stages considering opportunities surrounding AM.

Laverne et al. [5] based their conclusions on conducting a case study. It focused on the idea generation stage of DfAM. They requested the groups to propose innovative answers to a given design problem. After obtaining the solutions, the team would analyze the ideas while evaluating creativity, ordinality, and manufacturability. They tried to figure out if DfAM knowledge can significantly impact the generation of ideas. Groups under study were multidisciplinary to promote the inclusion of the following profiles in the analysis: engineering design, industrial design, and ergonomics. In this case study, the selected independent variable was the knowledge of AM: having group 1 as the control group (no knowledge of DfAM). Group 2 had no knowledge of AM, but they received helpful information, and finally, group 3 included AM experts.

A case study showed that a group with some basic AM info produced the most ideas in a design challenge, while AM experts produced the least number of ideas (opportunistic vs. restrictive thinking). Laverne et al [5] also concluded that dual DfAM methods yielded better results. Having AM knowledge promotes the generation of creative design solutions.

Design Heuristics for Additive Manufacturing Validated Through a User Study [6]

Combatting the knowledge barrier of AM that many designers have is essential. This paper attempts to create a design/educational tool that provides simple user-friendly “cards” with matching physical examples following the derivation method depicted in Figure 2:

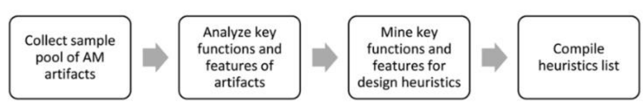


Fig. 2. *Steps taken to compile the Heuristics list [6]*

This paper provided a set of cards that aim to serve as AM-process-agnostic to cater to a significant audience and create a set of guidelines for the early design stages. A total of 29 Heuristics (as defined by Blosch-Paidosh et al. [6], a heuristic is “a context-dependent directive, based on intuition, tacit knowledge, or experimental understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution.”) cards served as a very general guide. Although it does not represent a complete overview of DfAM processes, it portrays the analysis of existing designs.

The authors collected several AM samples from multiple sources. The selection criteria involved 3D printed capability, excluding trivial examples. After collecting samples, the team evaluated the designs, key features, and functions. Authors grouped the cards based on the following scheme: part consolidation, customization, conveying information, materials, material distribution, embedding/enclosing, lightweight, and reconfiguration.

Blosch-Paidosh et al. [6] later continued with the analysis of this approach and conducted two case studies. They also applied specific heuristic guidelines to the existing products to showcase the potential improvements. Both novice and master designers participated in this study. Two groups were formed, randomly mixing levels of expertise. Two rounds were applied on each group: with/without heuristic cards. After conducting the analysis, the proposed tool proved effective.

Low-Cost 3D Printing for Science, Education and Sustainable Development [7]

This paper serves as an in-depth guide and introduction to AM, DfAM, and pre-print parameters for AM novices. It acts as a resource for many different AM configurations. It also indicates STEM and art fields that could benefit from this technology. The paper does not focus on the initial design stage but more on the slicing and post-design processing, missing a key aspect of DfAM. However, it does provide a good resource.

Being content-heavy, this paper could discourage beginners. During specific revisions, novices were intimidated by it.

Optimal Design for Additive Manufacturing: Opportunities and Challenges [8]

In this paper, Doubrovski et al. [8] discuss the 3-link Chain Model (3LCM) from the Central Paradigm of Materials and Science Engineering (Figure 3), which identifies the importance of design considerations during or before the initial design stage. The model illustrates how decisions made (or not) can critically impact material properties, structure, and thus performance down the road, avoiding failed prints, wasted time & money. 3LCM can help the designer work throughout the design following a cause-and-effect logic.

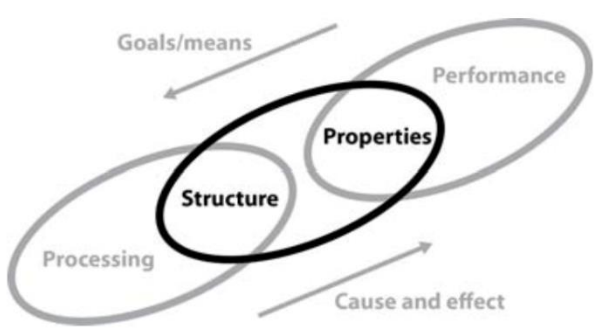


Fig. 3. *Three Link Chain model, 3LCM [5]*

Methods and Tools for Identifying and Leveraging Additive Manufacturing Design Potentials [9]

In this paper, Kumke et al. [9] review and analyze different design tools utilized during the DfAM process (including general design tools). Then they propose a method to scrutinize them to tailor for DfAM. Subsequently, the team puts these tools to the test to confirm applicability to the field of interest. Additionally, they design a digital, "easy-to-use" version of it, and present it to different experienced designers. The design aid tool is constituted of the following interactive elements (see Figure 4):

1. Dynamic network chart: Enables user/designer to identify capabilities, solutions, and keywords related to AM design complexities ("levers", along with their benefits for innovative products)
2. 3D Model: Supplies the user with illustrations supported by displayed additional information
3. Case study collection: Provides a set of examples of real-life AM parts.

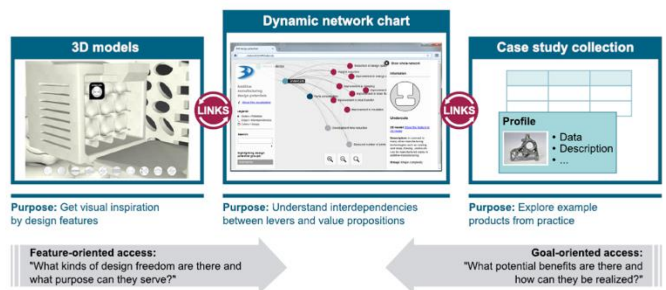


Fig. 4. *Interactive system for AM, interactive system, Reference [9]*

Running this experiment required multiple workshops. Designers used this tool and generated a particular product for the car industry. Participants got segmented into three groups:

- Group A: DfAM expert using the tool
- Group B: DfAM novices using the tool
- Group C: DfAM experts without the utilization of the tool.

The team set the following Hypotheses:

1. DfAM experts and novices require different sets of tools depending on their expertise level.
2. The newly developed tool facilitates the work
3. It also potentializes the level of creativity and feasibility of solutions provided by the participants involved in the experiment.

A team of experts would then evaluate the solutions provided by the groups, summarizing the results. Results showed that both

DfAM experts and novices did not consider the Dynamic Network Chart section of the tool to be very useful. Alternatively, the physical models were scored high (predominantly by the novice designers). Experts appreciated the set of extra information as add-ons to design methods, while novices were overwhelmed by it. After data analysis, hypotheses 1 and 3 succeeded, while hypothesis 2 was partially true. Further experimentation still needs running for the third since the population sample was relatively small.

IV. Key Takeaways

- Booth et al. [4] demonstrated that using the worksheet significantly reduces the number of failed prints. It confirms the positive impact of aid tools when working with DfAM. An in-depth approach using these methods can be beneficial to students and potential future designers.
- Following the structure set by Laverne et al. [5], DfAM efforts can be categorized utilizing the following classification methods: Opportunistic DfAM and Restrictive DfAM. As concluded, tools relevant to DfAM yield better results when considering a Dual approach (having both opportunistic and restrictive available for designers). AM knowledge represented by videos and pictures is particularly appreciated by designers.
- Blosch-Paidosh et al. [6] proved that including visuals promotes a better learning experience.
- DfAM is an iterative process in which decisions made will impact the final product, as suggested by Doubrovski et al. [8]. In Figure 3, the 3LCM shows a cause-and-effect relation between Processing, Structure, Properties, and Performance. The DfAM tool generated in this research can have an optimistic impact. It will serve as a point of reference, providing guidance to designers.
- As illustrated by Kumke et al. [9], having a tool that provides sufficient feedback, and AM capabilities can be highly efficient. The team also recommended avoiding saturation of information given to the DfAM participants, as this may overwhelm the designers (especially when time is restricted). Also, having DfAM theory available is practical, but what drives the most benefits is having physical examples and case studies. These propositions were made for future workshops:

  1) Keep a single design method to generate the ideas/solutions

  2) Provide design aid tools adequate to participant levels (novice and expert)

  3) Supply DfAM tool with time in advance, so the participants can feel comfortable using it

  4) work with mixed teams; experts can help novices from experience, and and they could also learn new perspectives from novices
- Existing literature and studies only provided brief methods which do not cover every guideline. User-friendly, interactive, and easy-to-understand tools are required to fully engage students or designers.
- There exists a clear gap in research and development on an in-depth and process-agnostic utility to educate and guide AM-novices with clear and concise DfAM guidelines.

V. Research Question and Hypothesis

With the rapid evolution of AM, there is a need to educate the upcoming workforce; those people need to comprehend:

- All AM processes with their strengths/weaknesses
- Engineering basics packaged with powerful problem-solving skills
- Design tools and guidelines to understand all aspects of AM
- How to apply creativity to designs

New openings in education are helping with this development. Some K-12 STEM programs now teach children CAD modeling, along with basic 3-D printing. The Maker community allows people to compete with DIY projects done with AM. Universities are incorporating DfAM courses into their curriculums for both undergraduate and graduate students [3].

With all this effort, there still seems to be a gap. Some people cannot access higher education, while other people need clear, thorough guidance. The following question arises:

How can design for additive manufacturing education be improved for targeting beginners in a user-friendly way?

Advertising towards AM demonstrates its capabilities (such as embedding, complex geometries...) and its advantage over TM. Available guidelines and tools are difficult to follow. They consist of research papers with minimal user interaction. Most people decide to ignore those tools and end up learning with trial/error without really understanding or having solid proof that the right thing is being performed. To reduce the number of failed prints and maximize the understanding of DfAM guidelines, this paper goes over a new educational tool. In this application, multiple criteria are used as interactive guidance to provide design feedback to the user. After going through this tool, the user will receive design improvement suggestions, AM relevance to the design (can it be printed? should it be printed?), and the top AM processes relevant to the specific design. The user will also be interacting with a 3-D model to promote understanding through visualization.

VI. Methods

We are producing an application in which the DfAM designer can screen the design in consideration. In this proposed method, multiple criteria will be used as interactive guidance to provide feedback using text and supporting images. An application will be developed in MATLAB, allowing us to provide a practical solution as DfAM evaluation criteria that can be presented in a practical manner. AM relevance to the design, along with top AM processes are issued after each iteration. Figure 5 represents the flow chart that the user will follow in order to achieve a successful print.

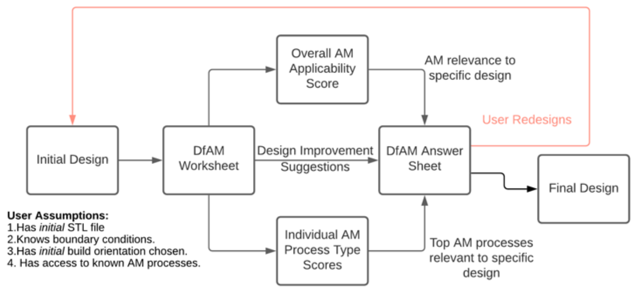


Fig 5. Tool Flow Chart

Process Weighting (Restrictive)
In order to correctly identify the most appropriate processes to recommend to the user, each process must have its respective restrictive elements ranked. For the processes themselves, we identified the 7 major AM processes as follows:

1. Material Extrusion
2. Material Jetting
3. Binder Jetting
4. Vat Photopolymerization
5. Powder Bed Fusion
6. Directed Energy Deposition (DED)
7. Sheet Lamination

Each process will have a respective ranking list that includes 10 chosen restrictive elements. These elements were chosen through analyzing the most common ones found in previous works (Design Heuristics, for example). The ten restrictive elements chosen are as follows (these correspond to a single question on the user end):

1. Internal Access
2. Overhangs
3. Bridges
4. Self-Supporting Angles
5. Sharp Corners
6. Cross Sectional Size/Area
7. Minimum Feature Size
8. Cross Sectional Ratio
9. Surface Accuracy
10. Structure Anisotropy

Therefore, there will be 7 separate lists (processes) within the program with each list having the 10 ranked elements. To rank these elements, an expert survey would be undertaken. At least one expert from each process would rank the 10 elements for their respective discipline to produce each list. Using the 7 lists, we would then average across to obtain our 8th list – overall AM.

Process Weighting (Opportunistic)
The seven major AM processes as listed previously will then be used to create opportunistic elements as well. The following seven opportunistic elements were decided:

1. Geometric Complexity (Freeform/Organic Surfaces)
2. Geometric Complexity (Lattice Structures)
3. Mass Customization
4. Part Consolidation (Relative Motion)
5. Multiple Materials
6. Embedded Internal Components

Process Weighting (Opportunistic)
Conversely, the weighting for opportunistic would be done internally rather than through the use of expert analysis. This is due to the greater subjectivity involved with evaluating opportunistic elements.

Tool Design & Logic
A prototype version of the design tool was built within MATLAB. This was done to not only visualize the user side (GUI design) but also to visualize the logic in the backend of the code to represent and test how the weighting, subtraction and ranking occurs. Figure 5 shows a screenshot of an example question generated in MATLAB. As shown, each question generates a new window in which there is a title that describes the question, a figure to visualize the question to the user, and three input options: a/b/c (bad/medium/good). Additionally, the STL object corresponding to the figure can be rotated by the user on the left, adding to the interactivity of the tool. As the user cycles through the three input options, the figure and 3D object updates to match the description of the selected option. This added layer of interactivity and explanation was chosen because the tool is being aimed towards with less AM experience who may not know terminology or specifics regarding opportunistic/restrictive design.

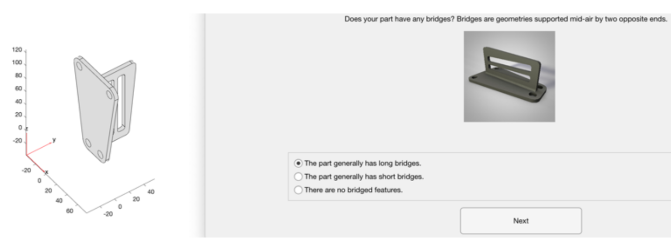


Fig 6. Design Tool GUI Design

On the backend, the code starts with nine separate variables (scores). Seven variables represent each process type, and the final two variables represent the restrictive and opportunistic scores. Figure 6 visualizes the loop that occurs as a user goes through each question. As an example, each score would begin at 100 for every variable. When a user answers a question, they will select a, b, or c. This acts as a multiplier which multiplies both the overall score and process-specific weights. For example, the user answers c for Question 4. Previously, we determined that for Material Extrusion this question ranked highest, and it is assigned a weight of 10, for example. We also determined that overall, this question was ranked 2nd highest for AM, and is assigned a weight of 9. If the user were to select option b, an overall score of 18 would be subtracted from the score from the previous question and similarly a Material Extrusion score of 20 would be subtracted from the score previous question. The process-specific weight would be calculated for the six other processes.

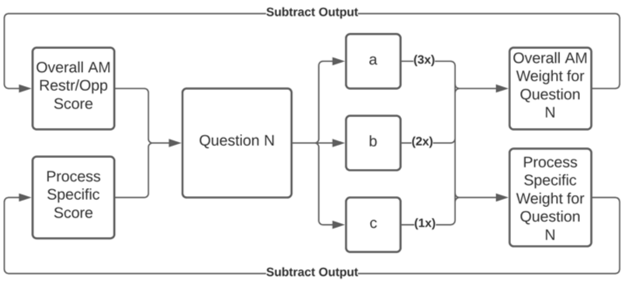


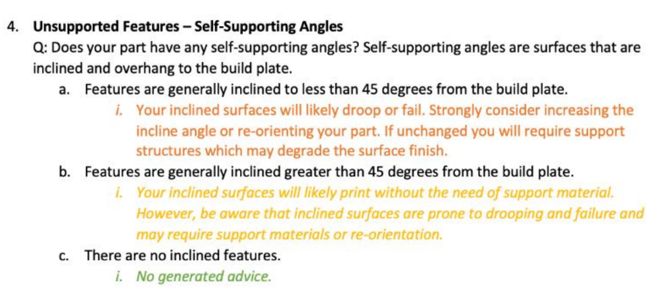
Fig 7. Code Logic for Each Question

This process is repeated for the opportunistic side as well. For the opportunistic questions, there will be process-specific removals. This means that the tool design will accommodate instances where a specific process would not generally allow for an opportunistic element. If a specific process is removed, it will not be presented to the user in the output.

After the user completes all 17 restrictive and opportunistic questions, we will output four items into the generated answer sheet.

1. The Restrictive overall score out of 100 ("Can I print this?")
2. The Opportunistic overall score out of 100 ("Should I print this?")
3. A ranked list of the top 3-5 variables (processes) based on the outputted scores from the seven process variables.
4. A list of generated solutions based on the user's input (a/b/c).

In the final version, a PDF will be outputted that contains the four previous sections. This will be written and outlined in a way that is easy to interpret and utilizes natural language to convey potential issues. For each question, when the user selects option a, b, or c a generated block of text is added to the output. Figure 7 displays an example of what would be generated for a specific question.



4. **Unsupported Features – Self-Supporting Angles**
   Q: Does your part have any self-supporting angles? Self-supporting angles are surfaces that are inclined and overhang to the build plate.
   a. Features are generally inclined to less than 45 degrees from the build plate.
      i. Your inclined surfaces will likely droop or fail. Strongly consider increasing the incline angle or re-orienting your part. If unchanged you will require support structures which may degrade the surface finish.
   b. Features are generally inclined greater than 45 degrees from the build plate.
      i. Your inclined surfaces will likely print without the need of support material. However, be aware that inclined surfaces are prone to drooping and failure and may require support materials or re-orientation.
   c. There are no inclined features.
      i. No generated advice.

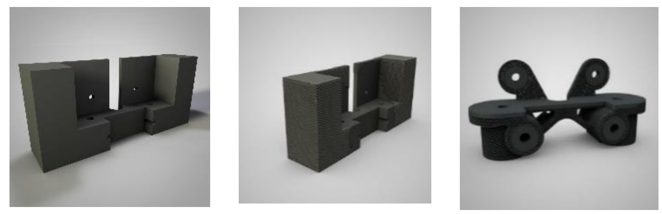
Fig 8. Example Generated Text Based on User Input

As demonstrated by Laverne et at [1], the proposed DfAM evaluation tool considers a dual approach by presenting to the DfAM designer both methods, opportunistic and restrictive:

Figures 9 and 10 show example images for each of the three options for restrictive and opportunistic elements.

The part generally has long overhanging features | The part generally has short overhanging features | There are no overhanging features

Fig 9. Example of Restrictive question from the DfAM evaluation tool. Question 2



The part is comprised of fully dense, continuous material. | The part uses lattice structures to reduce material use in areas with minimal loading. | The part relies heavily on lattice structures throughout, with density adjusted based on loading

Fig 10. Example of Opportunistic question from the DfAM evaluation tool

Based on this automatically generated answer sheet, the user now has a greater understanding of each design choice, they have been suggested relevant process types, understand their overall AM applicability for their specific design and have the tools to redesign if needed.

VII. Results and Discussion

Although only a prototype version was produced, the framework and concept exists to eventually create a fully finished product that enables AM novices to analyze and receive feedback for a specific part. The tool also incorporates the seven major AM processes to display the most relevant processes based on user input. Additionally, the tool will also accommodate both restrictive and opportunistic elements and removing specific process suggestions based on user inputs for opportunistic elements.

To date, this tool has been the first in providing all the previous features. The utilization of a digital interface to build the final product enables us to perform the automatic background calculations and automatic generation of solutions. Additionally, it simplified the user interface without the need of score boxes and tables as seen in prior publications. Furthermore, this tool has provided a set of tools to take processes-specific restrictions and opportunities into account. The basis of which is the weighting structure, which does not equally treat every element. Previous work has shown that both opportunistic and restrictive DfAM is crucial to understanding the entire picture of AM. Additionally, prior papers have discussed that various elements are more or less important than others, so our tool lays out the methods and calculations once the weights have been found.

VIII. Conclusion

The project provided us with a framework to enable designers, students, and engineering with limited AM knowledge a tool to analyze designs. The second aspect of the tool is the ability to educate the user through simply taking the worksheet.

Through research of past publications (Booth etc.), we identified key areas to analyze printability of parts through incorporating restrictive elements. We also utilized past resources such as the Design Heuristics cards to add opportunistic elements.

Additionally, we produced physical companion objects through CAD to visually represent every element's option. We identified a clear gap in prior work which relied heavily on hand-drawn images and lacked clarity for the user. The addition of the STL viewer in the GUI enables further interactivity for the user to understand each design element.

Future Work

As stated, the tool that we have created enables future work to be completed to refine the weighting and process recommendations.

The first step would be to survey an expert in each Additive Manufacturing discipline. The survey would be specific to their process type and would ask for instinctual responses. The expert would be prompted to rank each restrictive element on a 1-10 scale. After obtaining all the data, each process would be normalized on a 0-100 scale. Across all processes, the data would be averaged to provide the overall AM restrictive weighting scheme.

Next, the opportunistic weights and eliminators would be identified through an internal investigation of previous literature and discussion. Both would in turn provide the weighting functions for both the Restrictive and Opportunistic sections.

Once these are added and the tool is finished and refined to output an easy to read and interpret answer sheet, the testing can occur. In order to test the tool, there will be two main methods/ways of interpreting the tool test:

1. Test the improvement of the design process by performing a real-world user test. A group of students or designers would be prompted to design a specific part to be 3D printed. The part would be printed and analyzed for specific failures. The group would repeat the design experiment, using the DfAM worksheet tool. The new printed part would be compared against the control to identify if it improved the design process. Specifics such as number of redesigns after the tool outputs recommendations would be identified.
2. Test the design tool using case-study geometries in which process-specific printability is known. There are specific designs and geometries published which display the most relevant process type for that specific part. The exact design would be input into the tool, and we would verify that the output matches the expected process type.

IX. References

[1] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," *Bus. Horiz.*, vol. 60, no. 5, pp. 677–688, 2017, doi: 10.1016/j.bushor.2017.05.011.

[2] B. Berman, "3-D printing: The new industrial revolution," *Bus. Horiz.*, vol. 55, no. 2, pp. 155–162, 2012, doi: 10.1016/j.bushor.2011.11.003.

[3] W. Gao *et al.*, "The status, challenges, and future of additive manufacturing in engineering," *CAD Comput. Aided Des.*, vol. 69, pp. 65–89, 2015, doi: 10.1016/j.cad.2015.04.001.

[4] J. W. Booth, J. Alperovich, P. Chawla, J. Ma, T. N. Reid, and K. Ramani, "The design for additive manufacturing worksheet," *J. Mech. Des. Trans. ASME*, vol. 139, no. 10, pp. 1–9, 2017, doi: 10.1115/1.4037251.

[5] F. Laverne, F. Segonds, N. Anwer, and M. Le Coq, "Assembly based methods to support product innovation in design for additive manufacturing: An exploratory case study," *J. Mech. Des. Trans. ASME*, vol. 137, no. 12, pp. 1–8, 2015, doi: 10.1115/1.4031589.

[6] A. Blösch-Paidosh and K. Shea, "Design Heuristics for Additive Manufacturing Validated Through a User Study1," *J. Mech. Des. Trans. ASME*, vol. 141, no. 4, pp. 1–8, 2019, doi: 10.1115/1.4041051.

[7] C. F. and M. Z. Enrique Canessa, *Low - Cost 3D Printing*. 2013.

[8] Z. Doubrovski, J. C. Verlinden, and J. M. P. Geraedts, "Optimal design for additive manufacturing: Opportunities and challenges," *Proc. ASME Des. Eng. Tech. Conf.*, vol. 9, no. January, pp. 635–646, 2011, doi: 10.1115/DETC2011-48131.

[9] M. Kumke, H. Watschke, P. Hartogh, A. K. Bavendiek, and T. Vietor, "Methods and tools for identifying and leveraging additive manufacturing design potentials," *Int. J. Interact. Des. Manuf.*, vol. 12, no. 2, pp. 481–493, 2018, doi: 10.1007/s12008-017-0399-7.

X. Appendix A

DfAM Digital Worksheet App

A prototype version of the application is available here. To run the application, download the zip folder, expand and move to a local folder. Open "concept.m" and run the file. You will be able to go through questions and evaluate a design.