FIRST STEPS TOWARDS COLLABORATIVELY EDITED DESIGN FOR ADDITIVE MANUFACTURING KNOWLEDGE

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Abstract

Despite the broad coverage concerning the technological challenges, little research has been performed on the methods that enable designers to deal with Additive Manufacturing. At present, the challenge is to generate Design for Additive Manufacturing knowledge which goes beyond traditional solutions and to ensure that this knowledge is complete, correct and up to date. This paper reports on the employment of a wiki environment to support open-ended knowledge management. We applied this solution in an undergraduate prototyping course focused on exploring visual properties using AM structures. The results of the 32 students encompass unexpected designs while the knowledge on the wiki encompassed i) AM processes, ii) procedures, iii) artifacts. This forces us to rethink what should constitute DfAM.

Introduction

Additive Manufacturing (AM) is a maturing collection of production technologies also known as three-dimensional (3D) printing. Compared to conventional production, such as machining and injection molding, AM offers unprecedented possibilities in shape complexity and custom geometry. As the application of AM for the production of end-products is increasing, AM is having a growing influence on the product development cycle; the way products are designed, produced, distributed, consumed and recycled.

While AM is rapidly developing, industrial designers are facing several challenges in applying this manufacturing technology. It has been stated that the advantages of using AM are not yet understood by designers [1]. We argue that the issue is more fundamental: the current technological opportunities of AM are not yet fully known and, in addition, these possibilities are developing quickly, with new or improved processes and materials being developed on a regular basis. Within the AM research community, it is accepted that the development of Design for Additive Manufacturing (DfAM) methods is needed in order to allow designers to benefit from this manufacturing technology to the full extent [10]. However, despite the broad coverage of the technological challenges of AM, very little research has been performed on the methods that enable designers to deal with this game changer. Furthermore, among the DfAM approaches that have been proposed so far, very few have focused on the creative phases of the design process. In the context of this paper, we consider conceptual design as the most creative phase of the design process. Figure 1 shows the environment of conceptual design in the broader scope of the industrial design process, as illustrated by Horvath [2].
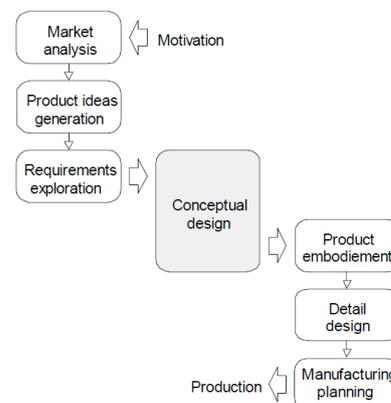

Figure 1: Environment of conceptual design

In developing a DfAM for the creative phases of industrial design we are facing several challenges. The rapid development of both the AM technology and the supporting software poses a risk of any DfAM method becoming obsolete within a short period of time. Furthermore, the possibilities of the currently existing technologies are still not fully discovered and documented. This makes us pose the following question: How can we generate DfAM knowledge that covers techniques and methods which go beyond traditional solutions? Although different DfAM approaches are being proposed in literature, none of the approaches is based on a collaboratively edited platform. Addressing the issues described above, we aim to examine how designers who are exploring AM structures with new properties can provide valuable contributions to the knowledge on the possibilities of AM and whether a collaboratively edited platform can support the documentation and use of the new methods, procedures, and designs. Demonstrating the feasibility of this approach, we present our results of an initial experiment among Industrial Design Engineering students using a wiki environment for collaborative editing of DfAM knowledge.

Emerging approaches to DfAM

Over the past years, as the application of additive technologies to production of end products has been increasing, several authors have identified the lack of design methodologies and design knowledge for AM, coining the term Design for Additive Manufacturing. Initially, most efforts to develop tools for designers included the development of support to select a suitable AM technology. Approaches ranging from knowledge-based systems [3] to neural networks and fuzzy logic [4] have been proposed to achieve this. Other methods that have been proposed support the AM production of components by assisting decision making such as choosing build orientation [5]. Furthermore a reasonable amount of literature can be found on the development of processes and algorithms to optimize structures for AM in order to achieve specific properties [6]. Commercially available software systems are limited to data handling, 3D design checking and generation of cellular structures within a volume. Focusing on design rules, rather than design methodologies, the thesis of Thomas [7] describes the development of design rules for selective laser melting. His work describes the evaluation of the geometric limitations of one AM system (SLM) through quantitative cyclic experiment. Based on the findings design rules were created which were then evaluated with design professionals.

While the abovementioned approaches are intended as design support, none of them truly assist a designer during the creative phases of product development. Maidin & Campbell recognized this gap and have described one of the most extensive efforts to solve this problem [8]. Therefore, the authors of this paper aimed at developing a knowledge-based support tool for designers for the creation of products for AM. A database of AM design features is used as a knowledge repository. A collection of such AM design features has been derived from examples from literature. In order to make this knowledge accessible to designers, these design features have been organized into a taxonomy with four top-level taxons being the key reasons for using AM. This database has been tested with design students and professional designers, showing that it can be helpful and inspirational during the conceptual phase of a design process.

A New Approach

The database described by Maidin et al. [1], which is at the core of their proposed method, depends on a centralized identification of design features from the designer's tacit knowledge and a centralized indexing of these design features into the database. However, the rapid global development of AM could make a centralized approach unmanageable. On one hand we see daily innovations in AM technology, such as materials, accuracy, surface finish, speed. On the other hand, we see a growing amount of new designs and smart applications of this AM technology. Therefore such a centralized scenario will pose challenges to the correctness, completeness and extensiveness of DfAM knowledge.

We propose a complementary method based on collaboratively edited content. Current online examples such as Wikipedia and Instructables [9] illustrate that, if provided with adequate tools, international communities can build and maintain a vast and up-to date database of knowledge. A vast amount of insight is

being created by designers when designing and manufacturing products or parts with AM. Therefore, the worldwide community of designers who design for AM are potentially a fruitful basis for a collaboratively edited DfAM knowledge base. Although collaboratively edited knowledge has been in existence for over a decade, it has not yet been applied in the context of Design for Additive Manufacturing knowledge. We intend to explore if the documentation and usage of their knowledge can be effectively facilitated by providing designers with a wiki environment. As an initial test of our approach, a pilot study has been executed in the context of an educational module. We aimed to answer the following questions:

- Is a wiki a suitable environment for documenting and using DfAM knowledge?
- How do designers interact with the wiki in terms of documentation and use?
- What knowledge is generated on the wiki?

Pilot Study

The pilot study has been performed during a 4 week course of a minor on Advanced Prototyping organized by the school of Industrial Design Engineering of the Delft University of Technology [10]. In total, 32 third year undergraduate students participated in the course, divided in four groups of 8 students. All students had good knowledge of AM and CAD modeling. The course was organized in a so called "carrousel" structure; each team worked on one of four selected topics for one week before switching to the next topic. This means that each topic was tackled by a new group each week, in four consecutive weeks. Each group of 8 students was divided into teams of two students. Two of the four topics were directly related to AM: visual properties of AM, and AM cellular structures. The two other topics were related to other aspects of prototyping: reverse engineering, and "objet trouvé".

This study was performed within the carousel topic "visual properties of AM". The assignment was relatively open, as the students were asked to explore techniques to achieve new visual and optical properties of AM-produced objects. In an overview of the literature, Doubrovski et al. [6] have shown that functional improvements, such as product weight, are being covered extensively in AM research, but visual properties remain unexplored. Since such properties are arguably just as important for industrial designers as other functional properties, this was an interesting new topic to explore in the context of the course. Initially, three sub-topics were chosen as a starting point for further exploration of visual properties, these being reflectance, optical fibers, and subsurface scattering. As described by Doubrovski et al. [11], there lies an opportunity to manipulate these properties in AM produced components, but the adequate knowledge and design tools do not exist.

As a platform for collaboratively edited content, the students were provided a wiki environment to document their progress, experiments, and results. The free service of WikiDot.com [12] was chosen, which is a free, simple, and relatively easy to use wiki. We have created an initial structure of the wiki which consisted of a main "home" page that links to 3 sub-pages which cover the 3 determined sub-topics: reflectance, optical fibers, and subsurface scattering. These pages initially contained a general description of the sub-topic and several envisioned challenges. Students from the first three teams were assigned to do explorative work on the topic and to document their developments and gained knowledge on the wiki. Students from the final team were asked to make a design of a product, applying the knowledge available on the wiki. It was allowed to edit the wiki at any time, both the content and structure. The students were not required to hand in any other form of written report apart from the wiki.

For the evaluation of our approach of using a wiki for collaboratively edited DfAM, after the completion of the course we have analyzed the constructed content on the wiki, the editing behavior of the participants, as well as the participant reflections on the use of the wiki. The wiki was inspected, considering both the content and the structure. The editing behavior was collected through the logs of user activity on the wiki. Finally, a questionnaire was used to collect the participant's reflections of the use of the wiki at the end of the course.

Constructed knowledge

Taking into account that the course was initiated when the wiki contained almost no information, and that the students were unfamiliar with the topic of visual properties of AM produced components, in four weeks, the four consecutive groups of students have designed and built remarkable results and the wiki has grown into a collection resources on the selected sub-topics. Below we discuss the emerged structure and content of the wiki.

Structure

At the end of the four-week course, the top level of the wiki structure has remained largely identical, with the sub-topics being present on the main page. The largest developments have taken place within the pages of the sub-topics. Figure 2 illustrates this structure of the wiki.
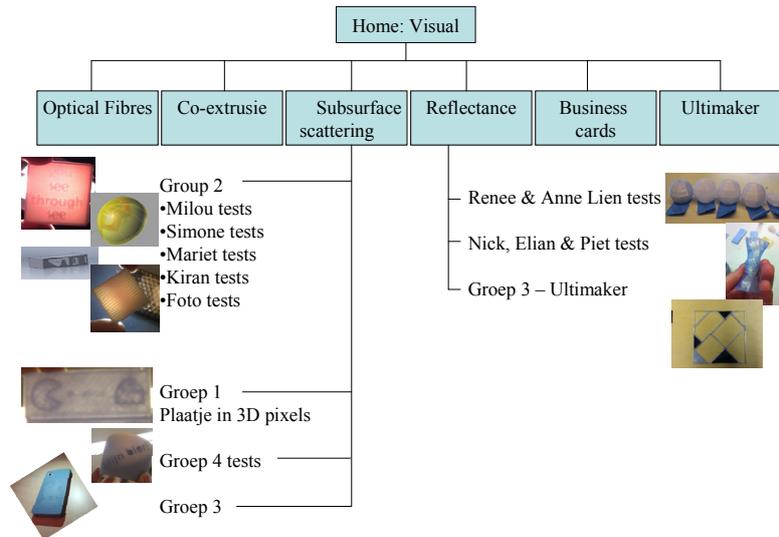

Figure 2: Emerged structure of the wiki.

As can be seen in the overview, some students have created new pages that are linked to the pages of the sub-topics while others have edited and expanded the page of the sub-topic itself. For example, the sub-topic of "subsurface scattering" has 5 child pages while the page of the sub-topic "optical fibers" has all of the content on the page itself and has no child-pages. Considering the above, we observe that the emerged structure is inconsistent and could be confusing. Furthermore, we see that the naming of the created pages is inconsistent and in some cases uninformative, having the name of the participants or the group number. Additionally we have found some pages that are linked to from an incorrect location, for example the description of the smartphone case with reflectance properties is linked from the sub-topic "subsurface scattering". The only form of active moderation by the authors has been the initial setup of the structure, no moderation was done during or after the project. The results described here indicate that this was not sufficient to maintain a clear and structured wiki.

Knowledge levels

Examining the wiki after the completion of the course provides us an insight in the content that has been generated by the participants. We have observed that the wiki has accumulated DfAM knowledge on different levels. Most of the knowledge on the wiki concerns concrete knowledge about specific processes, materials and applications. For example, descriptions are provided on how specific components have been modeled using the Grasshopper plugin for the Rhinoceros 3D software package, including detailed instructions on how to reproduce the built geometries (Figure 3). These descriptions have been used and further elaborated by students from later groups.
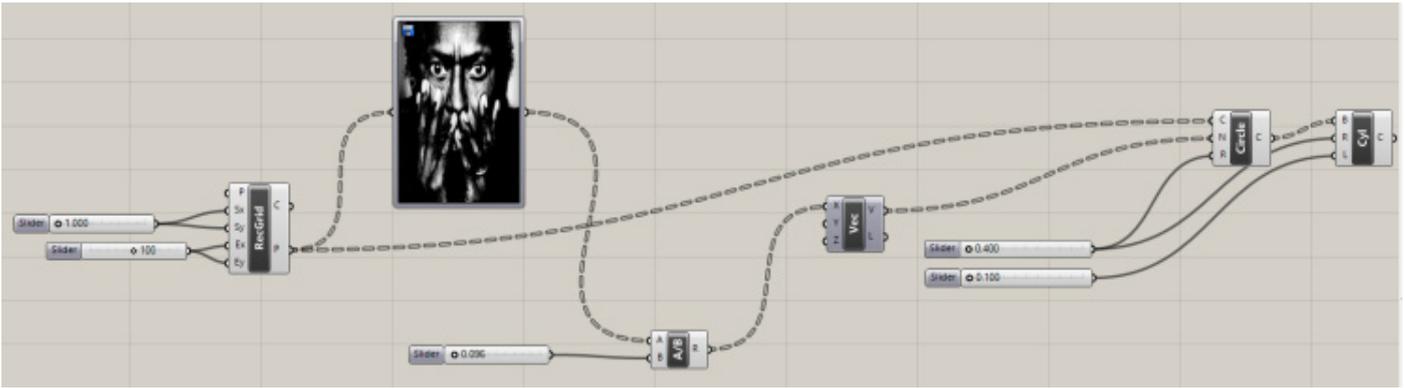
Figure 3: Wiki content, describing settings for the Grasshopper plugin of Rhinoceros 3D.

In addition to the processes descriptions of how specific visual properties were achieved, participants also provided descriptions of experiments on the wiki. These descriptions were valuable for successive groups who have applied the knowledge gained from these experiments. For example, members from the first group have tested different wall thicknesses of internal structures to see how light is passed through when using the VeroBlue material printed on the Objet Eden 260 3D printer, one of the test pieces is shown in Figure 4a. The test results, were used by members from the final group to design and 3D print a "beer glass cooler" that has internal features which result in a photograph with different shades when lit from behind (Figure 4b). Some participants have also added recommendations for further research on the visual phenomenon that they have explored. Also new ideas of applications of the visual properties have been described on the wiki pages.

a   b

Figure 4: test piece (a) and beer glass cooler (b).

Built models and designs

After discussing the knowledge on the wiki, in this section we discuss the outcome of the experiments and design activities of the students. These designs have been documented on the wiki and therefore can function as a source of tacit knowledge.

As already shown in figure 4a and 4b, several tests have been done whereby the internal geometry of a volume was designed to create different shades when the object is back-lit. Figure 5 shows a test piece in which a photograph can be seen.
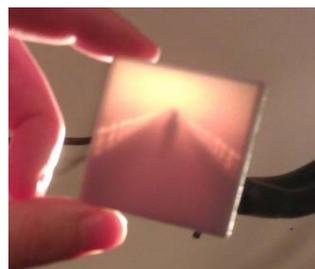
*Figure 5: Embedded photograph in a 3D printed sample.*

Another exploration into new visual properties was performed by manipulating the reflectivity of the 3D printed surface. The workflow to achieve this is based on the processes used for the beer cooler, where the Grasshopper plugin was used to sample an image and use the grayscale values as a parameter for cylinder diameter. In this example, instead of the diameter, the angle of the top surface is altered according to a grayscale value. Figure 6 shows a smartphone case with a surface consisting of embossed cylinders. As each surface under a different angle reflects different amounts of light, the result shows an image of an apple in different shades.

Figure 6: Smartphone case with reflective surface.

Based on the same Grasshopper workflow, another approach to visualize images has been explored by modeling a grid of small tubes through a solid sheet. Figure 7 shows the result of a 3D printed backlit sheet (thickness 2mm), illustrating a portrait. This effect is achieved by altering the angle of each tube is dependent on the grayscale value of the representing pixel. A full black pixel results in a 45 degree cylinder, while a white pixel results in a cylinder perpendicular to the plane surface.

These examples illustrate how knowledge on the wiki, describing a workflow to achieve a specific result, has been used to achieve new, completely different optical properties.
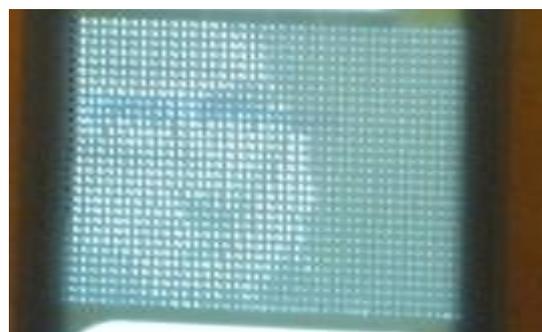
Figure 7: Back-lit test piece showing a portrait

One of the other topics that was explored is the Additive Manufacturing of optical fibers. Although this topic was only covered during one carrousel cycle, some exciting results have been achieved. Figure 8 shows samples that have been produced by extruding PMMA optical fibers using a RepRap Fused Deposition Modeling machine. The samples show that it is possible to produce objects with internal optical fibers allowing to direct light through a built volume.

Figure 8: Optical Fibers Produced with Fused Deposition Modeling

Wiki use

Editing behavior

By inspecting the logged edits on the wiki, we were able to analyze the user activity. As each of the four groups worked for one full week on the topic, the amount of edits of each group is labeled according to the day of the weekly carrousel. Figure 9 shows the amount of edits per day per team. For each team, most of the editing activity has been recorded during the last day of the week, before finalizing the project. Two groups started earlier, with initial editing on the third day of the week.
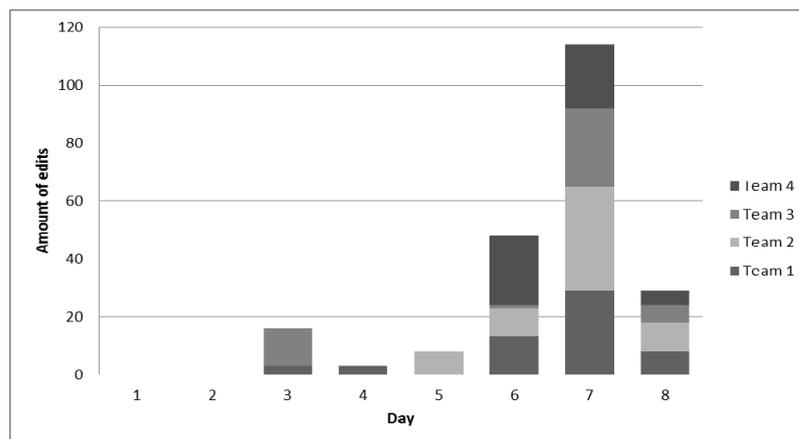

Figure 9: Page edits per team per day.

The fact that most most of the editing and documenting was done at the end of each carrousel round could be explained by the logic that as knowledge and results of the teams grew they documented more of these results on the Wiki. However, this could also imply that students used the wiki to report their work in a similar manner that is common in design education. This is discussed in the next section. Unfortunately we did not have the means to track the amount of page views of the wiki, such data would provide a some more insight in the use of the wiki.

Questionnaire

A questionnaire was handed out after the completion of the 4-week course to all students, 20 of whom responded. The aim of this questionnaire was to capture the i) students' reflection on the use of the wiki, ii) in which ways the wiki assisted the assignment, iii) how they think the wiki could be improved, and iv) how they envision future use of the emerged wiki. The questionnaire comprised of open questions, multiple choice questions and Likert scale questions. Because the first groups have worked with the wiki at the beginning of the

course, they were not familiar with the final state of the wiki. For this reason, before filling in the questionnaire, all students were asked to re-inspect the final wiki content. We discuss the main findings of the questionnaire below.

Four statements were provided related to the use of the wiki. The respondents were asked to score their level of agreement with the statements. Each statement was to be scored on a 5-point Lickert scale. We consider the upper two Lickert levels a positive feedback. The first statements were related to the use of the wiki during the project. Table 1 shows the percentages of respondents who have indicated to agree with the statements. We can see that the students reflect their use of the wiki mainly for documenting of their process, followed by the documentation of knowledge. The use of the wiki for the acquisition of knowledge is scored positive by 36% of the respondents.

Wiki use for:	Reflected use (%)	Envisioned use (%)
Documentation of process	82	90
Documentation of knowledge	72	90
Acquisition of knowledge	36	75
Collaboration with team members	23	25

Table 1: Reflected use of the wiki (n=20).

After the respondents were requested to inspect the wiki as it was at the end of the course, similar statements as the ones mentioned above were asked, but now related to the envisioned future use of the wiki. The responses show a similar ranking of agreement with the statements of envisioned use as the previous. We do see a significant increase of agreement with the statement that the wiki was used to acquire knowledge. Looking at the data we observe that during the project just 36% of the respondents have used the wiki to acquire knowledge for the project, while after looking at the more elaborated wiki, more than half of the respondents indicate to consider using this wiki for future projects. This increase in agreement is bigger for those, part of the first teams.

Nearly 40% of the respondents have indicated that the wiki did not help them during the course. Unfortunately most of the students who have indicated this, have did not provide an explanation. Among the few reasons that have been mentioned are the arguments that the wiki was only used to document own work and not for retrieving information. It is important to note that these responses were given mainly by students from the first two teams. In contrast, only 3 students from the last two groups have indicated that the wiki did not work for them. We can explain this by the fact that the use of the wiki was changing, as the amount of information culminated.

Responses to the question concerning possible improvements of the wiki included the ease of use of the used wiki platform, such as embedding of images and video. Several students proposed adding a search function and a navigation menu. Although most groups have created a wiki page for their team, yet while reflecting on the final wiki content, most students indicated that the wiki would have a better structure if the pages would be structured according to content and not according to team.

Discussion

Educational context
The experiment covered a weekly assignment on structures and visual properties. This was carried out by 4 consecutive groups of students, all sharing the wiki to keep track of insights and findings. It is obvious that this situation does not resemble a regular design project, and the level of commitment is differing from an industrial context. Furthermore, the knowledge necessary for this assignment does not require integration with other types of engineering and design, normally one of the main challenges in product design. Taking this into account, we cannot guarantee that professional designers will have the same relationship with this approach and

further experiments with professional designers are needed. However, the knowledge gained during the experiment surpassed known solutions and allowed a hands-on learning experience. As a didactical exercise, it does include apprehending new insights as design does. Also, many of the results resemble products, such as the beer holder. With 32 students, we are also able to generalize the findings to patterns of preferences and effectiveness.

Collaboration

This study concerns early experiments, starting with very little, to non-existent knowledge. As such, a sense of community is essential, yet the willingness of students to edit knowledge is not tested. The incentives of sharing knowledge on manufacturing among peers are not yet explored. Similar phenomena, such as webpages of FabLabs should be studied as well – these are typically maintained by members to describe case studies and skills. Aspects of collaborative learning and Communities in Practice [13] theories should be included in further studies. Current examples such as the wiki of RepRap.org shows that facilitating discussions among members of a community is essential. Furthermore, educational settings are different from personal use of wikis, i.e. the motivation to add, reorganize and alter information is linked to grading the student's assessment and not to social appreciation [14].

Wiki structure and moderation

Our objective is to establish an intertwined web of knowledge, with a several ways to navigate from hypothesis to solution, downloadable script/model and case studies. From the content of the wiki it is apparent that the participants are used to write reports of work done in chronological order. The documentation of just the results/data seems unfamiliar for the students. Overall these factors have made the content of the wiki less organized, but not necessarily incorrect. It has also made the wiki less expandable and not optimal for adding new knowledge. This is a typical challenge of wiki building and maintenance, some claim a hierarchical top-down structure such as a taxonomy is essential [15]. In this experiment, no active moderation of the pages was executed. As the experiment was done with a relatively small group, and took place within a short period of time, the entire wiki can still be overseen. It is clear that as the wiki would grow, structure and expandability will become increasingly important. An example of a database with active moderation is Thingiverse, this website offers ability to share 3D models in various formats, while designs are tracked but we need also for new ways of representing this information/kind of information. It includes a form of active moderation, e.g. to feature models on a front page.

Conclusion and Recommendation

At present, designers are confronted with a shortage of knowledge to make effective use of the possibilities of Additive Manufacturing. This article describes our efforts to understand how a DfAM method should be developed. In developing such a DfAM method we are facing several challenges: both AM technologies and supporting software are developing rapidly, posing the risk of any DfAM method being incomplete, or becoming obsolete within months. Furthermore, the possibilities of the currently existing technologies are still not fully explored and documented.

We employed a wiki environment in an undergraduate prototyping course as a pilot study for open-ended knowledge management for DfAM. In four consecutive teams, 32 students have experimentally explored the manipulation of visual properties of AM by modeling and building novel AM structures. Each team utilized the knowledge on the wiki and in turn documented their findings for future groups. As the data on the wiki expanded, it encompassed knowledge on different levels, such as procedures and artifact descriptions. The physical results showed a growth of sophistication, from simple tests to several products with remarkable visual properties.

We argue that building a DfAM method solely on currently available knowledge of the possibilities of AM is insufficient since AM clearly has many possibilities that are still unexplored. Based on this pilot study, we suggest several recommendations for the DfAM approach: it must offer a platform to allow mapping new knowledge on the possibilities of AM, and allow expansion of this knowledge triggered by the rapidly evolving possibilities of AM. Design acts, which were included in the pilot study, are proving to be a valuable source of such knowledge. Future DfAM methods should also address the organizations of collaboration and moderation, as well as conscious structuring of knowledge elements.

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