WORK IN PROGRESS: DEVELOPMENT OF EDUCATIONAL KIT FOR TEACHING ADDITIVE MANUFACTURING

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ABSTRACT

Additive Manufacturing (AM) is a unique manufacturing technology that is being rapidly accepted in various industries, leading to increased demand for experts who know to work with AM and how to design AM products. This led to a broader adaptation of AM in an educational context with various research on how to teach AM. However, most approaches are focused on teaching advanced AM application and Design for AM (DfAM), including both restrictive and opportunistic approaches, with little attention to specialised educational tools to show and teach the basic principle, possibilities and characteristics of AM. This paper presents the development of an Educational Kit for AM to address the gap and help teachers to explain the basics of AM, with a current focus on the material extrusion process. The Educational Kit is made of 17 models and accompanied cards explaining the essential characteristics of AM through short textual explanations, graphics, examples and manufacturing data. The Educational Kit for AM is intended to be used in introductory lessons on AM, so the novices in AM can quickly grasp the characteristics of AM and the basic terms used in AM before advancing to other AM and DfAM topics.

Keywords: Design education, Education, Additive Manufacturing, Design for Additive Manufacturing (DfAM)

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1 INTRODUCTION

Additive Manufacturing (AM), also known as 3D printing, is being adopted by the industry at increasing rates yearly (Wohlers, 2022). This is due to unique design capabilities and corresponding business opportunities enabled by AM and its principle of adding material only where it is needed to make a physical object from a virtual 3D model (Gibson et al., 2015; ISO, 2021). The design possibilities are manifested through four complexities of AM: geometrical, material, hierarchical and functional. These complexities enable designers to implement new forms and functionalities into their products (Gibson et al., 2015). At the same time, because the AM is a direct manufacturing technology that simplifies the production process and supply chain, new business opportunities emerged, especially in low volume - high complexity type of industries (e.g., aerospace, medical, etc.) (Diegel et al., 2019; Gibson et al., 2015). Therefore, AM transformed how we make and design our products (Seepersad, 2014). Consequently, the increasing use of AM in the industry led to increased demand for workers with knowledge of AM (Asiabanpour, 2019). This generated awareness for research on Design for Additive Manufacturing (DfAM) (Obi et al., 2022) and the need for AM education (Borgianni et al., 2022), especially in higher education (Borgianni et al., 2019; Prabhu, Miller, et al., 2020a; Stern et al., 2019), but also in primary and secondary education as well (Ford and Minshall, 2019; Pei et al., 2019).

Ford and Minshall (2019) reviewed where and how AM is used in teaching education, showing that AM is nowadays used as an educational tool in various educational surroundings, from schools and universities to libraries and maker spaces. AM is used to teach about AM itself through demonstrations and project-based learning but also to manufacture educational tools for teaching other topics. On the other hand, Borgianni et al. (2022) investigated the current state of education in the DfAM area through a survey among AM and DfAM educators, primarily at the university level. Their investigation of current practices in DfAM education showed that it is still a somewhat niche topic, but they emphasise the need to define a pedagogical model for AM education. While there is a growing number of AM and DfAM courses, Ford and Minshall (2019) underline the need for further improvement and development of teaching and curriculum materials to support the learning process and enable students to comprehend the AM, its possibilities, but also limitations.

However, while the literature sources are focused on investigating the education in areas of DfAM, advanced application of AM, or use of AM to educate in other areas, there is little attention on specialised educational tools for teaching the basics of AM. It has long been known that the use of hands-on models for active teaching can improve learning (Felder and Silverman, 1988), and the use of educational models has always been a part of teaching tools, as many educators recognise their importance (Lipson, 2007). Still, to teach the basic AM terms (e.g., what is layer height, support structure, etc.), educators often use ad hoc models and parts that are available to them to explain the topic to students. Such objects do not always clearly depict the AM characteristic being explained, or one object is used to explain multiple AM characteristics, thus hindering the conceptualisation of individual terms.

Therefore, this paper proposes the conception of AM Educational Kit, made of multiple physical AM models and accompanying cards through which basic concepts of AM are explained. The intended application of AM Educational Kit is in the early stages of AM Education, as the first point of contact with the formal AM education, before progressing to advanced application of AM and DfAM. The paper is structured as follows. First, a brief overview of AM and DfAM education is presented in Section 2. The method for developing AM models is described in Section 3, while Section 4 presents the developed AM Educational Kit. Finally, Section 5 summarises the developed kit and outlines future research.

2 BACKGROUND & RELATED WORK

While AM-related research is constantly developing both AM technology itself, as well as DfAM methods and tools for leveraging AM possibilities in the design of new products (Gao et al., 2015; Thompson et al., 2016), there is a growing need to transfer the new knowledge to students through education (Asiabanpour, 2019). Therefore, a growing number of universities are including DfAM in their education, either as a stand-alone course or as a part of a broader course on manufacturing, engineering, and design (Borgianni et al., 2019). In addition, literature sources report different ways of learning about AM and DfAM, from learning through project-based approaches, such as building an

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AM machine or design challenge, to lecture-based approaches and the use of models created with AM in the classroom.

An early example of adopting AM is the addition of rapid prototyping into the engineering curriculum to support learning about innovative manufacturing processes and the development of students' conceptual designs (Helge Bøhn, 1997). Today, a common form of DfAM education is through project-based learning, where students are taught about AM and DfAM and their applications (Borgianni et al., 2022). For example, Go and Hart (2016) demonstrated in-depth learning of AM through lab sessions where students learn about AM through interaction with AM machines. However, this way of learning by doing is not feasible for large sessions with tenths or even hundreds of students at the time. Similarly, Günther et al. (2020) used project-based learning to teach AM where groups of students (2-3 students per group) had a task of assembling the AM machine, creating their first AM objects, setting up process chain, and optimising their AM objects. This kind of educational setup positively impacted students who got practical experience with AM and DfAM, but it requires many resources to implement.

Stern et al. (2019) described a five-step pedagogical model to introduce AM in education made of an initial introduction to AM, a practical engineering project, an introduction to materials used in AM, mechanical and structural testing, and a redesign engineering project. They applied the five-step model and showed a positive impact on students' motivation and engagement, as well as the development of engineering skills. Prabhu et al. (Prabhu, Bracken, et al., 2020; Prabhu, Miller, et al., 2020a, 2020b) investigated the influence of DfAM on designers' creativity. They conducted an experiment with three groups of participants, where groups were given lectures on restrictive, opportunistic, or dual (both restrictive and opportunistic) DfAM. After the lectures, participants were given a design challenge through which their knowledge was assessed. The evaluation revealed that when teaching only restrictive DfAM, generated ideas were "more useful", meaning they were compliant with the technical capabilities of AM and could be easily manufactured. On the other hand, dual DfAM encouraged a generation of ideas with higher technical excellence and overall creativity (Prabhu, Miller, et al., 2020b).

To promote the use of hands-on models manufactured with AM, Lipson (2007) proposed the creation of a library of educational models so both educators and students can download, and manufacture required models on demand. This library is intended to gather educational models for a variety of subjects. Similarly, Leary et al. (2015) focused on engineering educational models, where physical models of technical systems are created using AM to enhance students' engagement with the curriculum topics. Howard (2019) used 3D models in the classroom to teach students statics through hands-on experience using AM models. Here one group of students interacted with AM models during lectures (live class), while the other group (online class) only saw the demonstration of the model. Students who handled the AM models found it a helpful learning tool, while students that did not have an opportunity showed a great interest in acquiring their own models. Howard concluded that this proof-of-concept provides confidence that AM models can help students conceptualise the topic of interest.

The overview of current achievements shows great interest in AM and DfAM education and the use of AM in teaching various topics. However, current reports on AM and DfAM education often focus on project-based learning, requiring small cohorts, laboratories, and various AM equipment. Such educational approaches are often only feasible for small classroom lectures, while large lectures are often focused on passive learning. The examples of using AM models in the education of various topics showed the benefits of tactile experience during lectures. Therefore, there is potential to use AM models to promote hands-on experience and active learning when teaching about AM in classes with a large number of participants. The application of active learning has shown increases in student performance in science, engineering, and mathematics (Freeman et al., 2014). However, regardless of the evidence in support of active learning, most educators use traditional methods, especially with a larger number of students in a classroom (Deslauriers et al., 2019; Stains et al., 2018). Therefore, this paper addresses the identified gap by proposing the AM Educational Kit, intended for teaching basic AM terms, in large-scale introductory lectures on AM and DfAM, by enabling students to have hands-on experience through interaction with the AM models.

3 DEVELOPMENT OF AM EDUCATIONAL KIT

The development kit was motivated by the existing evidence that learning is enhanced when students have an active experience during lectures (Deslauriers et al., 2019; Meyers and Jones, 1993). A four-step method was used to develop the AM Educational Kit (Figure 1). The process started by reviewing

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the AM literature, focusing on the Material EXtrusion (MEX) process (ISO, 2021) to extract the basic AM terms. This study is focused primarily on the development of AM Educational Kit based on MEX for a few reasons. First, MEX is widely spread AM technology used in industrial, hobby and educational environments (Gao et al., 2015; Gibson et al., 2015). Due to its simplicity and affordability, there are many cheap desktop AM machines on the market. Therefore, for many users, the MEX is the first point of contact with AM, and MEX is often used in education. Furthermore, the focus on MEX will ensure the feasibility of all physical models on the same (affordable) machine, hopefully influencing educators to replicate the kit for use in their classrooms, but also enable relatively fast and cheap manufacturing of a greater number of kits to be distributed during classes with a large attendance. The initial list of AM basic terms comprises 17 terms (support structure; infill pattern; stress concentrations; infill density; mass reduction; overhangs; lettering size; assembly manufacturing; layer height; anisotropy; multicolour AM; hole size; materials; multi-material MA; wall thickness & gap size). The list of AM terms is not comprehensive in a way that depicts all terms related to AM or MEX. Instead, it is tailored to the current introductory lectures on AM and DfAM conducted by the authors, as the kit will be used in a lecture on AM and DfAM with an already defined curriculum. The students typically enrolled on this course are third and fifth-year mechanical engineering students. These students typically had previous courses on conventional manufacturing technologies, where AM was mentioned but without in-depth coverage and without consideration for DfAM. Therefore, the students have limited previous knowledge about AM (exceptions are the hobby users of AM) and no knowledge about DfAM. Therefore, the basic AM terms in this kit aim to level the knowledge about AM and its characteristics as an introduction to a broader DfAM lecture.

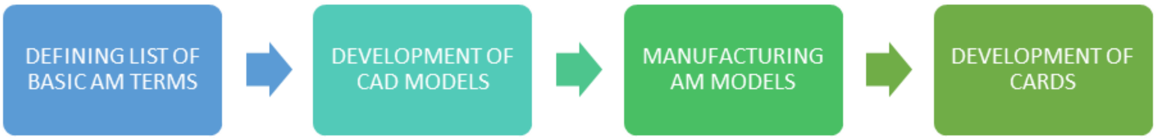

Figure 1. AM educational kit development method

After defining the list of basic AM terms, the second step was the development of CAD models that would display identified terms. During the development, an aim was to create models that are approximately up to 50mm x 50mm x 50mm in size, as this should allow for easy holding in hand but also ensure all the details are both visible on the model and feasible with low-resolution MEX machine. After creation, each CAD model was put in a slicer to simulate manufacturing details and was reiterated if the desired AM term was not clearly expressed. Afterwards, each model was manufactured on a desktop MEX machine using different materials (PLA, PETG, ABS, TPU). This was a highly iterative process involving multiple iterations until the desired AM term was clearly shown on the model. Once the CAD models were created and all AM models were manufactured, the physical objects became a primary element of representation in the developed kit. The intention of physical models is to promote active learning through hands-on experience (Deslauriers et al., 2019; Freeman et al., 2014; Meyers and Jones, 1993).

The final step of kit development was the creation of cards that accompany each model. The cards further explain each term by providing an image of a model, a short description, or a comparison of manufacturing data. An image of the model enables easier identification of each AM term. At the same time, textual description offers an easy way of explaining the intended meaning, especially if a high level of abstraction is needed, as students can recognise words as a concept and derive their broader connotations (Goldschmidt and Sever, 2011). The final element of representation on cards is manufacturing data. The manufacturing data provide additional insights into each term and is particularly notable for terms like layer height and infill density, where depending on the chosen manufacturing parameters, there is a significant difference in manufacturing time or amount of used material. This information helps students understand the pros and cons of AM and its basic characteristics regarding manufacturability.

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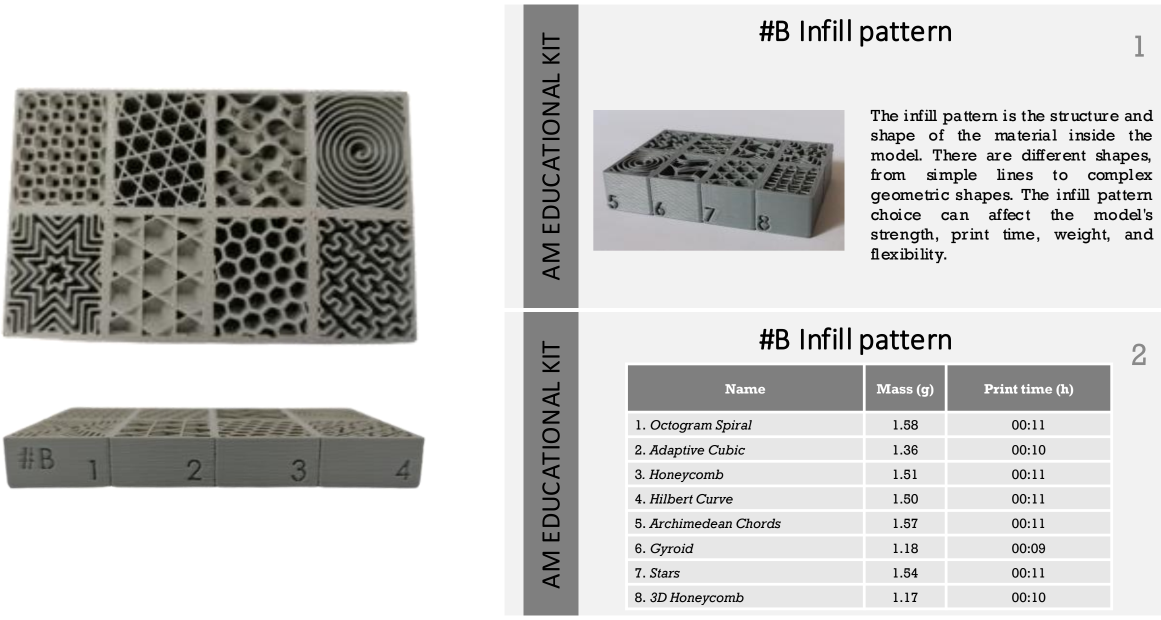
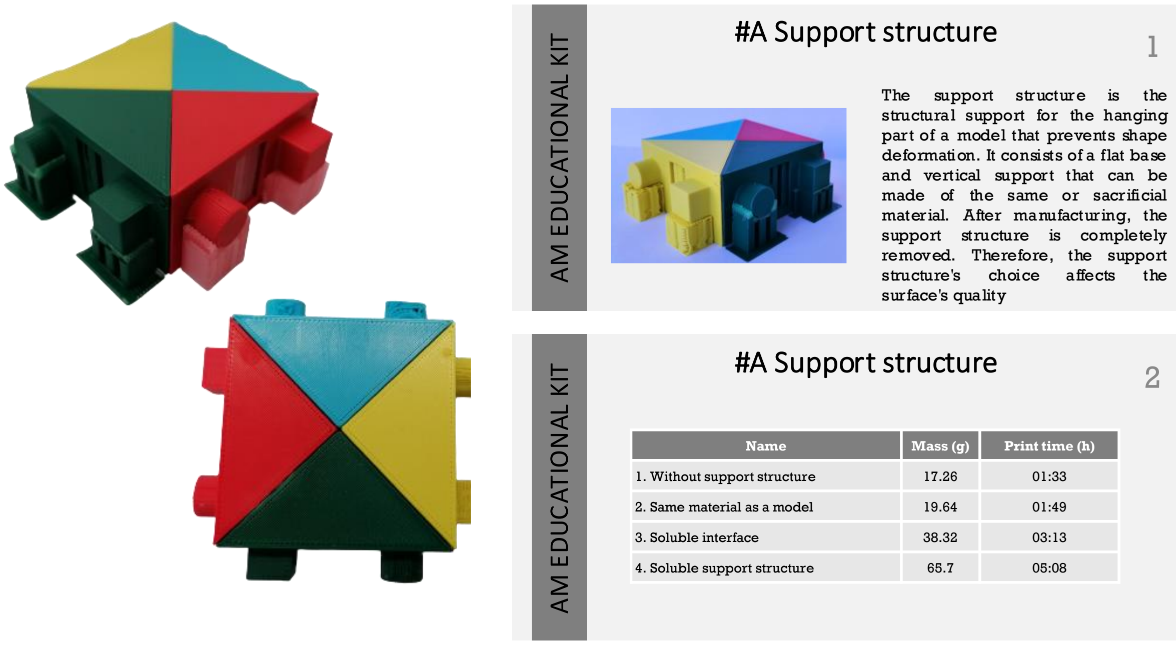
4 AM EDUCATIONAL KIT

The developed kit comprises 17 models showing AM/MEX terms used in authors' introductory lectures on AM and DfAM. Examples of AM Model for a description of the term "Infill Pattern" and "Support Structure" are shown in Figure 2 and Figure 3. Infill is used to create a structure inside the AM part. Different patterns are used to create robust structure, but each pattern has a trade-off between manufacturing time, material usage and strength (Dudescu and Racz, 2017). Therefore, to demonstrate the internal structure and its shape, AM model is made of eight different infills, showing both 2D and 3D infill shapes. On the side of the model is an embedded ID of the AM model (#B) and additional numbers that correspond to manufacturing data on the card (1-8). The corresponding card accompanies the model. On the front of the card are marking for the side of the card, AM Term and its ID, a picture of the model and the description of the AM term. On the back side are marking for the side of the card and the table with manufacturing data. For each of the eight infills, there is a name of the infill pattern, the mass of material used and the manufacturing time.



Name	Mass (g)	Print time (h)
1. *Octogram Spiral*	1.58	00:11
2. *Adaptive Cubic*	1.36	00:10
3. *Honeycomb*	1.51	00:11
4. *Hilbert Curve*	1.50	00:11
5. *Archimedean Chords*	1.57	00:11
6. *Gyroid*	1.18	00:09
7. *Stars*	1.54	00:11
8. *3D Honeycomb*	1.17	00:10

Figure 2. AM model for infill pattern



Name	Mass (g)	Print time (h)
1. Without support structure	17.26	01:33
2. Same material as a model	19.64	01:49
3. Soluble interface	38.32	03:13
4. Soluble support structure	65.7	05:08

Figure 3. AM model for support structure

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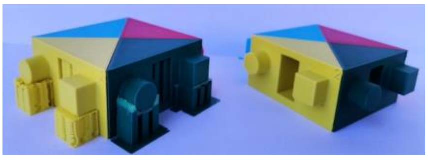
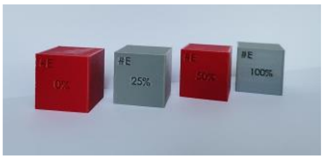
Similarly, the support structure is used to manufacture the part's overhanging areas by providing a surface on which material can be deposited (Diegel et al., 2019). Furthermore, in MEX processes, the support structure can be made of the same material as a part, a different sacrificial material or with a combination of the two where only contact layers are made with a different sacrificial material. The AM Model for support structure (#A) is shown in Figure 3, and it is made of two parts, one with a support structure attached and one where support is removed to show the surface after removal. Each part contains four sections where the three types of support, as well as the overhang made without support, are shown. Manufacturing data on the back of the card illustrate the amount of material used and manufacturing time for each section.
In the same manner, AM Model and the corresponding card are created for each of the 17 identified terms. Table 1 presents all models, with their identification letter (ID), term and description of the term, as well as a picture of the final AM model. All AM models were manufactured using Prusa i3 MK3s desktop printer with multi-material MMU2s unit. To obtain the AM models and accompanying cards, please contact the corresponding author.
The envisioned use case scenario is to distribute multiple sets of AM Educational Kit during lectures among students. The students will then be able to hold the models in their hands and observe the characteristic of the AM while the teacher explains the terms during the lecture. This should facilitate the understanding of the AM, enable limited experimentation with the models, and provide a tactile experience about AM for the students.

Table 1. AM educational kit - description and physical models

#ID	AM Term – Short description	AM Model
#A	**Support structure** - The support structure is the structural support for the hanging part of a model that prevents shape deformation. It consists of a flat base and vertical support that can be made of the same or sacrificial material. After manufacturing, the support structure is completely removed. Therefore, the support structure's choice affects the surface's quality.	
#B	**Infill pattern** - The infill pattern is the structure and shape of the material inside the model. There are different shapes, from simple lines to complex geometric shapes. The infill pattern choice can affect the model's strength, print time, weight, and flexibility.	
#C	**Stress concentration** - The layer-by-layer manufacturing can create stress concentration when there is a sudden significant change of area between layers. To reduce stress concentration, gradual change of area is achieved by adding fillets and chamfers.	
#D	**Infill density** - AM enables the selection of the infill percentage. A lower percentage of the infill saves material and print time, while higher percentages result in stronger models.	
#E	**Mass reduction** - By adjusting the infill percentage, the model’s mass is directly affected while maintaining or improving the model’s properties. AM enables the printing of completely hollow, very light models.	
#F	**Overhangs** - If there are hanging parts with a low angle of inclination, the material gives way and collapses at the overhangs. Reducing the angle leads to increasing deformation of the model. It is recommended to use support structures or change the print orientation to prevent deformation of the model.	

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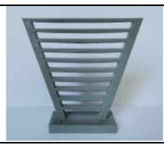
#G	**Lettering size** - Relatively small font sizes are readable on the vertical sides of the model, while the quality of small font sizes will be poor on the top side. Markings can be embossed or recessed.	
#H	**Assembly manufacturing** - By choosing the appropriate clearance between parts of the assembly, it is possible to manufacture parts of the assembly in one print without the need for later assembly.	
#I	**Layer Height** - The choice of layer height affects the quality of the surface of the model, the printing time and the amount of material needed. The lower the layer height, the better the quality of the surface, but the printing time is slower, and the amount of needed material increases.	
#J	**Anisotropy** - By choosing the orientation depending on the direction in which the force acts, we can reduce the intensity of anisotropy. A tile on which forces act perpendicularly to the created layers will crack sooner than a tile on which forces act in the direction of the layers.	
#K	**Print orientation** - Print orientation is possible in the x, y and z-axis. Depending on the shape of the product, by choosing the orientation, we can influence the quality of the surfaces, the amount of supporting material, and thus the production time.	
#L	**Bridge** - On bridges, shape deformation occurs due to gravity pulling the layers of material before they cool down, making it difficult to achieve straight bridges.	
#M	**Multicolour AM** - Multicolour enables the manufacturing of attractive products. To achieve the multicolour characteristic, different areas of products are made with different materials, thus requiring AM machine with the possibility of changing material in a single layer.	
#N	**Hole size** - By choosing the hole dimension, we influence the dimensional accuracy and quality of production. Holes with dimensions that are too small will turn out deformed and thus lose their dimensional accuracy.	
#O	**Materials** - Different polymer materials with different properties, such as strength, resistance to abrasion and humidity, are used for the MEX process. Among the most represented are PLA, ABS, SILK, NYLON, TPU and others	
#P	**Multi-material AM** - The MEX process enables the production of products made from two or more different materials. It is possible to choose a material for one area of the part that is different from the other, depending on what properties need to be achieved.	
#R	**Wall thickness & Gap Size** - When making walls and gaps using the MEX process, it is necessary to pay attention to their thickness for an optimal result. If the dimensions are small, the shape will be deformed, or gaps can be fused.	

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5 SUMMARY & OUTLOOK

The above-described AM Educational Kit is a work in progress, and it is the first iteration of the kit. The intended purpose of the kit is to enable hands-on experience to promote active learning (Felder and Silverman, 1988) with AM in introductory lessons about AM and DfAM. The kit is an addition to images and a potential substitute for ad-hoc models used for teaching the basics of AM. Furthermore, as the use of AM machines in classes with large attendance is troublesome due to the speed of AM and time needed to manufacture multiple objects in one- or two-hour time slot for a lecture, the educational kit presents a viable alternative for providing hands-on experience in such settings, as it can be easily multiplied in advance and distributed among a large number of students.

The presented work has some limitations. First of all, the current version of the kit has 17 models for a selected set of AM terms. Therefore, the models do not depict all AM terms but rather a concise set of terms used in authors' introductory lessons on AM and DfAM held every year. Furthermore, the set is based on the capabilities of MEX processes due to their widespread application in education and affordability (Gao et al., 2015). Hence, some AM terms specific to other AM processes, such as the removal of excess powder or part nesting, are not included. However, following the described method, one can create additional models.

The second limitation of the presented work is the lack of validation. The validation is planned for the spring semester of the academic year 2022/2023 when the lecture on DfAM for third-year mechanical engineering students will be held. Approximately 100 students typically attend the lecture. Hence the planned validation will include the experimental and control groups to evaluate the influence of AM models on learning outcomes. Furthermore, the interaction of students will be observed, as well as their subjective opinion of the usefulness of the models as a teaching tool. Additional attention during the evaluation will be on the representation elements of AM models and their suitability for intended teaching purposes. Previous studies showed that physical models are highly rated as they provide more information than other forms of representation (Gonçalves et al., 2014). However, the appropriateness of combining physical AM models with accompanying cards with images, text descriptions and manufacturing data must be tested. Following the observation that will be gathered, a new iteration of AM Educational Kit is planned that will be distributed among the research and teaching community.

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