DESIGN TEACHING INTEGRATING ADDITIVE MANUFACTURING CONSTRAINTS

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ABSTRACT

Additive manufacturing (AM) processes are now integrated in industry. Therefore, new methods to design AM parts taken into consideration capabilities and limitations are necessary. It is very difficult for teachers to effectively guide students with ideas emerging from generative design tools. AM requires significant preparation and compromises. Topological optimization is also used depending on requirements. A significant impact on the final part quality is related to the part orientation and geometric dimensions. Therefore, this white paper focuses on detailed design steps to prepare future technicians and engineers to design for additive manufacturing. Active teaching pedagogy guideline is proposed. Students have to think in 3D and use analysis tools to create and validate the optimised design. They use immersive tools to review constraints and model diagnostic algorithm to generate data. Present approaches with design guidelines and tools enable to create AM rules based on it. Questionnaire shows that students need explicit knowledge information. Features recognition and geometry diagnostic are mandatory for complex model. Immersive tool helps to evaluate post-processing. They can now relate AM product-process relationship.

Keywords: Additive Manufacturing, Requirements, Decision making, Training, Visualisation

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1 INTRODUCTION

As researchers in additive manufacturing (AM), we recognize the importance of equipping students with a comprehensive understanding of the technology and its potential applications. To achieve this, we have developed a course on "Design for Additive Manufacturing" (DfAM) that incorporates active pedagogical methods and immersive devices. The aim of this course is to enable students to design complex, multi-functional, and optimized products using AM by the end of the program. Students will be able to identify opportunities for additive manufacturing, apply DfAM principles (Gibson et al, 2015), and use optimization software to create innovative and high-performance products. To achieve successful DfAM, it is important to consider various factors such as part orientation, support structure, and material selection. For instance, designing parts with self-supporting features and minimizing overhangs can improve the print quality and reduce the need for support structures (Mokhtarian et al., 2020). One of the challenges of teaching AM is the difficulty of conveying complex geometries and manufacturing constraints to students. To overcome this challenge, we have incorporated active pedagogical methods and immersive tools into the course, which have been shown to facilitate conceptual thinking and promote deep learning. The course is structured around three key questions: Which concepts are they learning on DfAM? Which connections would make students with processability? What will be the opportunities and transfer in industry? These questions guide students from superficial knowledge to deep learning and help them to identify the key concepts and connections necessary for DfAM. We have also included case studies and examples of successful applications of AM to illustrate the opportunities that the technology offers. This approach has been effective in engaging students and helping them to understand the potential of AM. In the section on the design process, we provide a detailed explanation of how the design process differs for additive manufacturing. We discuss how conventional design processes need to be adapted to incorporate AM principles for industrialization and how optimization software can be used to create complex geometries for specific objectives, such as light weighting (Generative Design software based on functional surfaces and external constraints).

The teaching method described in this article is based on active pedagogy such as Problem and Data-based learning. Problem-based learning (PBL) is a student-centered learning method. Students learn a subject through experience. Hard real problems are presented and solved (Aalborg, 2015). It facilitates students' mastery of concepts and principles. The PBL process does not focus on problem solving but allows an active development of other skills and attributes. Acquiring knowledge, working in a team and improving communication are called soft-skills that can be experienced. It was used in the context of AM design method. Data-Driven Learning (DDL) has been recognized as one of the most important aspects of content and value creation in the 21st century (Rezaei etal., 2020). DDL is a great way to match theory with practice. Students analyze the data to see patterns, meanings, or other aspects. DDL transforms the learning environment in which teachers are "consultants" rather than the only authorized holders of knowledge. Additive manufacturing is related to data and it can be manipulated. Complex data and its analysis can determine form/process/material interactions with graphics.

Immersive tools (IMT) (virtual reality or augmented reality) are presented: immersion, interaction and imagination by Burdea and Coiffet (2017). For example, users can fully immerse themselves (as if they exist) in a certain environment without physically creating it. Users can also interact directly with their environment, making finding and solving problems faster and easier. IMT is hence incorporate real-world concept in AM such as support removal. IMT first appeared in the field of gaming, but is now used in surgery (Moro et al., 2017), anatomy (Mathur, 2015), or music education (Innocenti et al., 2019). This technology starts to be used in engineering and education. The main research activity aims to validate the project. Halabi [(2019) uses IMT in digital prototyping to evaluate student projects. Abulroub [(2011) used IMT to conduct project evaluations, while Castronovo (2019) identified errors and tested students' skills in game-based construction projects. Wolfartsberger (2019) uses IMT to easily assemble and disassemble product parts during design review. In the DfAM courses, IMT is used to visualize concept with 3D Experience (Dassault CAD/CAM platform). Experimentation is necessary to critically evaluate and propose explicit knowledge. Analysis algorithms are included to show features and provide information to the students, facilitating the integration of AM rules with practical design skills. Design, process simulation and Immersive tools are integrated in the platform. It helps to get a 3D shape visualization and process chain intuition.

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In summary, this paper presents a course on DfAM that aims to equip students with the skills and knowledge necessary to design complex and optimized products using AM. First, the course is presented and pedagogical steps are illustrated. Then, it includes case studies and examples of successful applications of AM, and discusses how DfAM courses need to be adapted to incorporate AM principles for real product industrialization. Finally, the article emphasizes the importance of translating interactions between numeric and life-cycle analysis, AM constraints to their function and familiarizing students with the opportunities that AM offers.

2 DFAM COURSES

2.1 Structure

The described course is created for third-year undergraduate students in Mechanical Design and Manufacturing at the University of Bordeaux, France. The aim of the entire course is to teach students the relationship between products/processes/materials. From his background, they have an in-depth knowledge of advanced design, including surface and parametric design, and have seen additive manufacturing processes. This development comes from the necessity of Industry 4.0. As new engineers develop new products using advanced manufacturing technologies, it is important to connect design and AM. Students can:

- Apply knowledge on additive manufacturing, and reverse engineering in a variety of domains (apply)
- Investigate process parameters for effective additive manufacturing (create)
- Differentiate principles and opportunities behind additive manufacturing technologies (analyze)
- Select an appropriate AM technology based on optimization criteria (eg. cost, quality, time/ available resources) (evaluate)
- Specify functions, objective and geometric parameters with a design for additive manufacturing (DfAM) for the development of new products (specify)
- Communicate effectively and work in a team environment (share)

Instructors introduce AM technologies. Industrial processes are introduced with material, possibility, advantages and disadvantages. There is also, in the case of "3D Printing" and Laser Powder Bed Fusion, immersive tool examples providing information about the process such as layer size, hot-end temperature, acceleration-deceleration effects (Figure 1). It helps to understand causes and effects in the process. Benchmark feature objects are introduced.

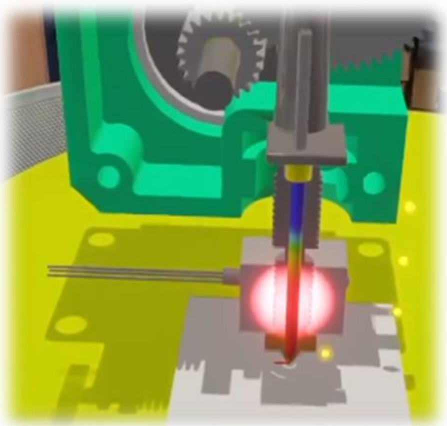

Figure 1. Modelling hot-end temperature of FDM process

Then, active pedagogical methods are used in three steps (cf. Figure 1): (STEP A) Benchmarking, (STEP B) Dissection/Selection of Features and (STEP C) DfAM. This course has been conceived as a learning game to motivate students. A group is composed of 5 students. The first module (A) teaches to students: is support necessary? What should be the angle during printing? What is the best part orientation? What is the impact of these constraints on the manufacturing, the precision, the

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roughness, the properties? The second module (B) allows to evaluate design rules based on 3D printed part with geometric dimensions and tolerancing (GD&T). The idea is to highlight causal effects, which ensures all requirements link to specific manufacturing constraints. A pattern analysis tool is introduced. Finally, the third module (C) introduces a DfAM method with a topological optimization. Process chain is then explored for a new product design that is suitable for AM. Skills are evaluated for each steps and students applied on a project.

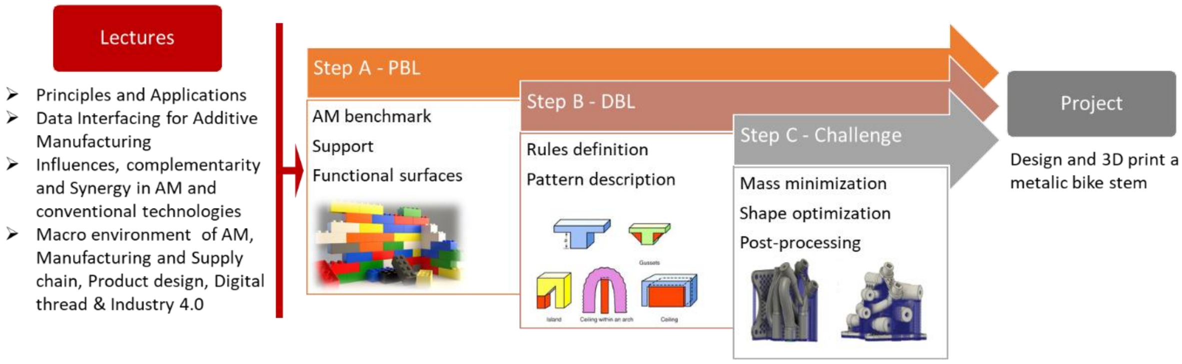

Figure 2. Course configuration – Lecture – Step A/B/C – Project

2.2 Step A

The description of Step A provides an overview of the activities involved in the approach, including the selection of processes, materials, and the evaluation of product manufacturability. However, to improve understanding, it would be beneficial to include more details regarding each of these activities. Rebaioli and Fassi (2017) outlines three types of AM benchmarking, including geometric, mechanical, and process benchmarks. Geometric benchmarking is used to measure part features such as tolerances, accuracy, repeatability, and surface finish (Cajal et al., 2013). In addition, it is important to analyze the mechanical properties of materials and process-related parameters (). The first PBL activity in the course focuses on the capabilities and limitations of AM technologies. Students actively explore AM considerations by measuring features on a benchmark, which assesses one of the three metrics of resolution, accuracy, and surface finish. The benchmark consists of a castle inspired by Vauban's architecture, which is composed of six branches. Each branch is identical, with one process parameter and is produced on six different machines. The castle is also composed of six zones, including basic geometric primitives (cube, pyramid, sphere), and AM features (overhanging, holes, pockets), each with a specification sheet. The accuracy and repeatability of each zone are analyzed (Figure 3). The benchmark artifact is easily disassembled, and features are measured using a 3D scanner or a coordinate measuring machine. By providing more details regarding each activity involved in Step A, students will gain a better understanding of the selection process, and how it can affect product manufacturability. Additionally, the use of a benchmarking activity, such as the castle example, provides a practical way to demonstrate the capabilities and limitations of AM technologies.

Component		Evaluation items
Square		External linear accuracy, parallelism, perpendicularity
Cylinder		External roundness, cylindricity, concentricity
Angle		Angularity, surface roughness
Wall		Small linear accuracy (thickness)
Sphere		Internal or external sphericity
Base surface		Flatness, surface roughness
Fine features		The ability to make details
Hole	Square	Internal linear accuracy, parallelism, perpendicularity
	Round	Internal roundness, cylindricity, concentricity, aspect ratio

Figure 3. Vauban's architecture enabling the benchmarking of AM machines and component evaluations

In problem-based learning (PBL), the problem to solve should be relevant and authentic to the real-world context, challenging enough to engage students, and aligned with the learning objectives of the course. For Step A, the problem to solve is related to the design and production of a specific product

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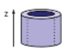
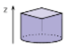
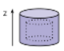
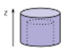
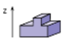
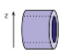
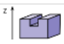
using additive manufacturing technology. For example, students can be tasked with designing and manufacturing a logo of their teams using the same AM process and material as previously. To evaluate students for Step A, there are several assessment methods used, including: (1) Rubrics: evaluation of manufacturability of the logo design (expert analysis: 5 points); (2) Peer evaluation: structured peer evaluation form based on a graph which is representative of defect geometric defects localization (other teams: five points); and (3) Reflections: Students write reflective essays on their experiences and learning in Step A. This can provide an opportunity for students to demonstrate their understanding of the concepts and skills related to the activities in Step A (Teacher: 10 points).

2.3 Step B

DfAM is a process that involves the simultaneous consideration of various design criteria and rules to produce functional and high-quality products using AM technologies. Laser Powder Bed Fusion technology is chosen as strong experiences can be shared by teacher. The selection of appropriate AM processes and materials is closely tied to the shape and design of the product, and the mastery of interconnected criteria in an integrated design approach is essential for successful DfAM. To ensure that students have a thorough understanding of good design and manufacturing practices for AM, an early introduction to these concepts is provided during the product definition stage. This is critical for minimizing manufacturing costs and difficulties. To facilitate this learning process, a set of criteria (Table 1) is presented, and their manufacturability, precision, and properties are discussed. They were in fact measure and discuss in STEP A. Architectural features cards are also provided, which help students understand the causes and consequences of these criteria in terms of process, cost, and properties (Additive Architect Game).

To help students develop AM rules, an example is presented in which they generate relationships between a pattern and a defects library. This involves defining AM rules using a standardization map, based on the eight rules of Mbow et al. (2021). The next step is to generate data (DDL application) using 3D printed parts made with different build orientations. Students classify defects based on observations with the naked eye or with the use of metrology tools. They also list features, referring to the previous benchmark analysis work (Douin et al., 2022). Each group analyzes three objects and shares their development, completing a table of AM rules. For example, they may locate a defect within two branches with a half-sphere shape, which occurs before merging with the branches. They can associate the defect with "bridge", which corresponds to a rule of overlap limits. This illustrates the collapsing of a surface and the idea of optimization using "Gothic" arches should occur. The three parts are design for machining, casting or additive manufacturing.

Table 1. List of patterns (Douin et al. 2022)

Scheme	Name	Complement	Scheme	Name	Complement
	Extrusion	Orthogonal		Vertical hole	
		Swept			
	Variable section volume			Overhang surface	With support
	Hollow volume	With support			Without support
		Without support		Bridge	With support
	Shell	Right side up			Without support
		Upside down		Rib	
	Horizontal hole	With support		Slot	
		Without support			

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To validate their results, students discuss with other groups to generate rules using a literal structure that enables mathematical representation of their rules. The structure involves defining an action, evaluation concept attribute, and shape entity/features. Once coded, the results can be validated for different objects, ensuring that the results are logical based on the part analysis (Figure 4). The 3D model is chosen, the rules is coded following action, attribute and entity. It provided a surface map. For instance, if the rules are to minimize the shadows. They can locate the orientations with the minima. If necessary, assistance is provided to refine their understanding with specific manufactured parts. By following this procedure, students gain a thorough understanding of DfAM and are equipped with the skills necessary to produce functional and high-quality products using AM technologies.

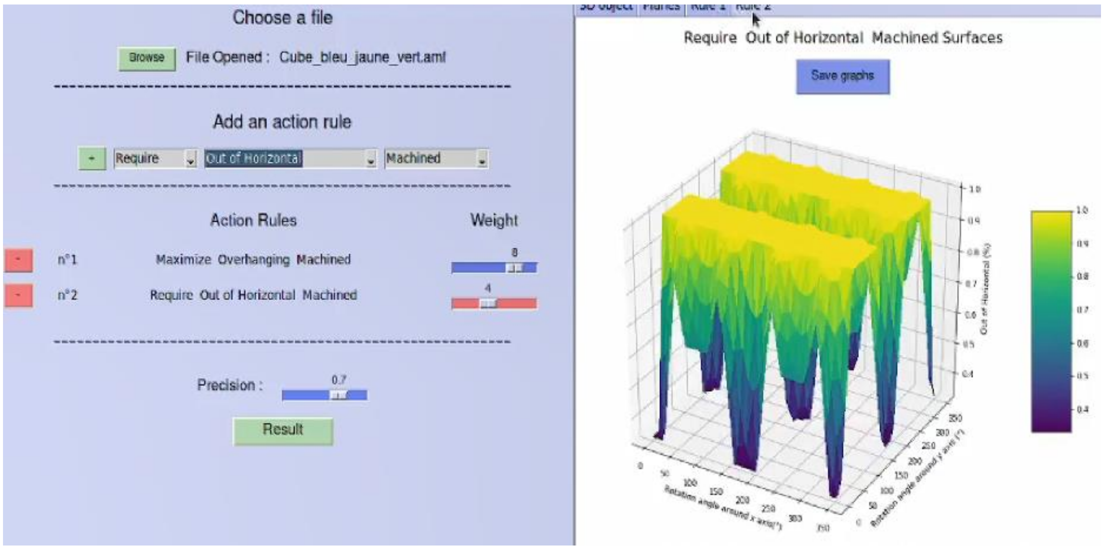

Figure 4. Proprietary tool to generate rules with attributes chosen – Map for each criterion can calculated with alpha and beta angles (orientation)

With data-based learning, students can be evaluated based on their ability to understand and apply the rules of additive manufacturing to produce high-quality parts. As they work through the process of analyzing 3D printed parts for defects and features, they can demonstrate their understanding of how the design and manufacturing criteria interact to influence the functionality and quality of the product. Additionally, as they develop AM rules based on their analysis, they can demonstrate their ability to apply critical thinking skills to solve problems related to additive manufacturing. Their ability to create and validate mathematical representations of their rules can also be used to evaluate their understanding of the principles of additive manufacturing. The evaluation is done through assessments such as practical assignments. They have five objects. They need to propose an orientation and justify (four points/part).

2.4 Step C

The goal of the curriculum is to teach students about the factors that affect print quality and economics in AM. The theoretical concepts covered in STEP A and B provide a foundation for STEP C practical problem-solving. Students work on designing block collectors from the AM specification, which are metal blocks with holes that allow fluid to flow from one source to another. The design of the block collectors is approached through a problem-based learning (PBL) framework, where students start with an idea and use 3D sketching tools to draw their concept. The first design concept focuses on the input/output (I/O) location and general space definition, with consideration of process constraints to meet functional requirements such as fitting, weight, and flow. The goal of the PBL exercise is to reduce weight by removing unwanted material from the block collector, resulting in a "minimal" set of pipes. Students identify the functional areas and discuss DfAM principles to minimize weight while AM maintaining manufacturability. Figure 5a provides an example of the redesigned cylinder with compression bars and analyzed using the shell tool, and various tools are recommended for use in the DfAM process. Validation of orientation and feature recognition are also discussed using rules and previous tool steps.

Once design ideas are finalized, students discuss the print orientation for the manifold based on functional surfaces and post-machining, as this can affect function and complexity of operation. If

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unsure, students are encouraged to save their work in STL format and present their idea with arguments to an expert. Using AM software, they can visualize indicators such as proximity or thickness for their current design (Figure 4b) and supports (Figure 4c), which teaches them the importance of quickly switching between different tool applications. Sensitivity analysis of thin wall or thin gap can be performed to prevent bad printing of metallic parts, as well as evaluating the post-processing through immersive time, imagining hand operations and avoiding inaccessible zones for support removal or finishing (Figure 4d). Students can critique the support structure based on accessibility, tools, and forces that is necessary. In summary, the curriculum aims to teach students the theoretical concepts and practical applications of AM design using a PBL framework. Through the iterative design process, students learn to optimize the design for weight reduction while maintaining functional requirements and manufacturability, using DfAM principles and various tools to validate the design. They also gain experience in evaluating post-processing operations and support structure to ensure successful printing of their designs. They ensure in this task an DfAM workflow.

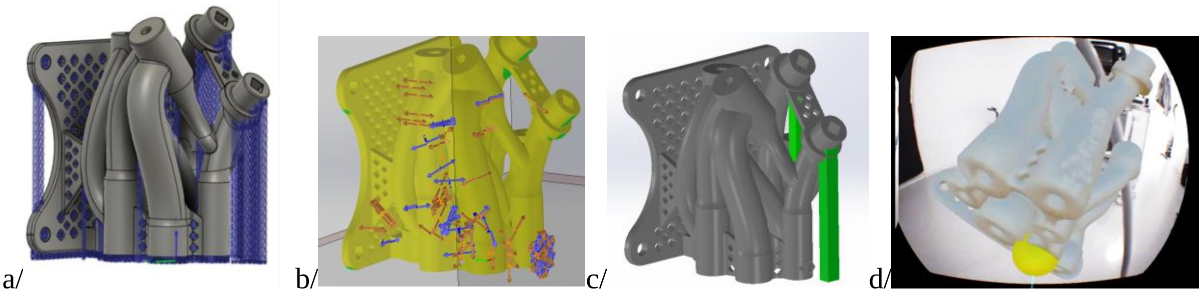

Figure 5. Concept based on thin wall, thin gap, overhang analysis to optimized manufacturability and support removal through IMT integration

After completing their designs, each team presents and receives feedback from other teams on their concepts. This process encourages students to develop critical thinking skills by evaluating the advantages and disadvantages of various ideas. Based on this feedback, teams then propose a solution to address any issues that were identified. The design strategies employed by the teams are varied, but all aim to justify their choices through quantitative analysis and iterative design. As there are many different solutions that can be effective, each with unique implications for part quality and function, there is no one "correct" way to design for AM. To facilitate learning, faults and challenges are intentionally not corrected during the course.

Part are printed. Students gain valuable experience by attempting to remove support material, for example, and understanding the importance of post-AM operations. Through observing geometric deviations and defects and analyzing feature and parameter associations, students also develop expertise in process and material selection. The printed parts are classified based on weight, design and post-process criteria with student. The marks are based on the criteria. This hands-on experience is a key element in demonstrating the usefulness of DfAM in a meaningful way.

3 DIFFICULTIES AND VALIDATION OF THE PROPOSED APPROACH

The active pedagogical strategy utilized in this study was found to be effective in imparting theoretical knowledge. Specifically, STEP A and STEP B provided a theoretical background for STEP C, which can be further developed for specific AM processes. As a result, there was no poor designs and new concepts were introduced in STEP C. One notable aspect of the study was that the students were responsible for evaluating and critiquing each other's designs, which forced novices to evaluate their designs and iterate until they were of high quality. Active pedagogy was driven by generating and applying rules, and note-taking or feedback documents were necessary for students to absorb the information effectively. However, the results also highlight the need for formalized knowledge at the end of the courses. The rules need to be written and a feedback address to students.

The challenge of Step C allowed for students to check their design and utilize 3D visualization tools, leading to mostly manufacturable designs. 85% of students requested 3D visualization tools. Several questions were interested about references for post-processing or residual stress evaluation tools should be included. Process simulation should be utilized to further improve the results. The evaluation consisted of a survey of the participants, conducted after the completion of the design steps. The survey

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contained a set of questions related to the participants' experience and learning outcomes, as well as their feedback on the workshop content and structure. STEP A was evaluated on feature characteristic and limitation for manufacturability, support, accuracy, defects, STEP B was on part orientation optimization and STEP C was part observation and quality. The survey was administered online, and participants were given a week to complete it. The sample size was 56 participants, who were recruited from a local university and had low degree levels of prior experience with additive manufacturing. The students followed and validated the DfAM courses. While the evaluation provides some insights into the participants' experience and feedback on the workshop, there are several limitations that need to be addressed. First, the survey questions were clear but not obvious (several orientations were possible), which makes it difficult to assess the validity and reliability of the data collected. Several justifications can be proposed and clear indicators need to be justified. It is important to ensure that the questions are clear, relevant, and unbiased to obtain meaningful results. It is difficult to provide 3D object representation and ask question on it. Second, the sample size of 56 participants is relatively small, which may limit the generalizability of the findings. Ideally, a larger and more diverse sample would be needed to ensure that the results are representative of the population. Several level will be tested. Finally, the survey introduced bias. For instance, two groups proposed an AM-adapted manifold design. One group did not succeed to print their part. Others got defects. The survey did not relate the similar proportion. Theorical and practical understandings are related and difficult to evaluate.

Overall, while the evaluation provides some useful feedback on the course. A questionnaire was administered after STEP C, consisting of questions related to 7 topics: Sufficient explicit knowledge, Usefulness of explicit knowledge, Modification of design based on tacit knowledge, Inability to improve the design, Association of general information with explicit knowledge, Need for explicit information with tools, 3D visualization tools. The results showed that students found the teaching process time-consuming for absorbing and generate explicit knowledge, and preferred transmissive interaction instead. Based on the evaluation data, it seems that the students had some difficulty in applying tacit knowledge to improve their designs for additive manufacturing (AM). Specifically, 35% of the students found it impossible to improve their designs with explicit knowledge alone and expressed a need for expertise and information related to their design. Therefore, it is essential to provide students with the necessary tools and expertise related to their designs in AM. The Additive Manufacturing Consulting network consists of international experts and consultants who leverage the potential of AM in any environment. The consulting covers all relevant AM topics, from business evaluation based on industry all the way through to user training. Additionally, they present a need for expertise in DfAM, and 90% of survey respondents believed academics would have the most significant impact on the future manufacturing workforce by teaching students to have a deeper knowledge of DfAM (Chen et al., 2017). Step C allowed students to work with DfAM thinking in order to better exploit the potential of AM, but the complexity of the problem was apparent due to the students' lack of experience with Laser Powder Bed Fusion technologyy. Additional data and expertise were needed to comprehensively develop successful industrial cases. 85% of students found features analysis tools to be necessary, and all students wanted to experiment with the processes. Part examples were insufficient and students mixed their design methods with conventional processes. Printed manifold enables a first experience and improvement were suggested after part printing. All students asked for AM printing experiences during DfAM courses. In terms of improving the learning experience, incorporating more hands-on activities and practical exercises enhance understanding of AM processes. They suggested solutions after manifold prints. Providing clear guidelines and feedback mechanisms can also help students to better understand their strengths and weaknesses. Knowledge formalization is required. Based on responses, it is clear that incorporating hands-on activities and practical exercises, offering clear guidelines and feedback mechanisms, and promoting collaboration and peer review can enhance the learning experience for students in additive manufacturing. Formalizing knowledge in additive manufacturing through education and training programs, such as the qualification system launched by EWF can help operators and engineers develop the necessary skills for successful AM applications (Sotomayor et al 2021). Also, active pedagogical strategy improved their skills over time and offer opportunities for collaboration and peer review foster a more supportive and engaging learning environment (75% of success was team work).

Finally, three questions were asked in introduction. The students are learning about DfAM, which involves designing products in a way that considers the unique capabilities and limitations of additive manufacturing processes. They are also learning about the entire additive manufacturing process chain, including conception, design, data preparation, and post-processing. This approach enables connections between part geometry and processability. They gain an understanding of how their designs can be manufactured effectively and efficiently using AM processes. This study suggests that the students have gained critical engineering skills in the product design domain that can be applied to different industries. Additionally, the course's methodical approach, which led students to generate design rules and gain hands-on experience with prototypes through team projects, could help prepare them for real-world industry applications of additive manufacturing. It is important to recognize that AM is a rapidly evolving field, and ongoing education and training will be necessary to keep up with the latest advancements and techniques. Providing access to resources such as workshops can help to ensure that students have the tools and knowledge necessary to succeed in their careers.

4 CONCLUSION AND PERSPECTIVES

This white paper proposes a novel approach to integrating AM constraints into the detailed design phase, using a game mode that promotes interaction and teamwork among students from different disciplines. The goal of this course is to raise interdisciplinary awareness of AM and enable factor-based design, which considers both design objectives and manufacturing constraints also to identify potential problems and solutions early in the design process. The course's methodical approach has enabled students to develop critical engineering skills, particularly in the product design domain, using PBL and DDL methods that can be tailored to different skill levels. During the course, students gained insights into various topics, including the entire AM process chain from design, data preparation, and post-processing. They obtained both tacit and explicit information, which helped them generate design rules and gain hands-on experience with prototypes through team projects. They manage to generate light weighted manifold adapted to AM process.

Although the effectiveness of this approach was formally evaluated, a questionnaire was analyzed to identify students' opinions and needs. The results suggest that explicit information, along with AM analysis tools, is required to improve students' understanding of AM and enhance their design skills. The key message of the course was to put the right material in the right place for the best reasons, which the students seemed to have grasped well. However, they need tools for feature recognition and processability. In conclusion, this approach provides a promising avenue for DfAM teaching and integrating AM constraints into the design process and fostering interdisciplinary learning among students.

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