A NEW APPROACH TO TEACH CONCEPTUAL DESIGN INTEGRATING ADDITIVE MANUFACTURING CONSTRAINTS

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Abstract. In the context of the Industry 4.0, new processes have appeared, such as the additive manufacturing (AM) process. Therefore, new approaches to design parts have to be developed to integrate process constraints. It is very difficult for teachers to effectively guide students during conceptual design for AM, even though various idea generation techniques and methods are available. AM requires an important preparation and compromise in design phases. In addition, design need to be generated in a digital environment. Among the various steps, critical impacts on the final part quality are linked to part orientation. So, this paper focuses on the conceptual design phase to educate future technician and engineers to the design for additive manufacturing. Pilot-study on the teacher's role interacts through active pedagogical tool with students. They need to think in 3D and create directly in 3D. The propose education development use an immersive tool to consider the process constraints. Thereby, students need to deal with an AM process chain. New approaches are analyzed based on the design guidelines for Additive Manufacturing, which were developed by the students themselves. Also, the students estimated opportunities and limits linked to product-process relationship. Finally, the success of the new course contents and form is reviewed by a student evaluation.

Keywords: immersive tool, teaching, additive manufacturing, design, game

1 INTRODUCTION

Students' learning needs to endure and make sense of complexity now and in the future. Students should go beyond the learning of facts and skills. Learning knowledge and skills is difficult despite available data and information. It's easy to spot details but hard to see patterns. For students to think what Additive Manufacturing (AM) can offer, they need opportunities to head up. They should generalize, summarize, and draw conclusions by looking at their learning in a holistic way. Factual and conceptual levels of thinking is proposed by intentionally designing active learning about additive manufacturing. They can construct understanding and facilitate transfer to a new era of Industry 4.0. Three questions can be proposed to help students go from surface to deep learning:

- From the facts or skills being taught, which concepts are they learning?
- Which connections between concepts would make students?
- What opportunities for application and transfer can be designed to help students?

These questions define different levels of conceptual thinking. If students do not have a strong understanding of specific concepts, they will struggle to see patterns and make connections between them. Likewise, active pedagogical methods and immersive tools are developed to teach "Design for Additive Manufacturing" (AM) [1]

Current courses in engineering design are well adapted to conventional design and manufacturing processes. First, students have to identify customers' needs and define the functional analysis. The system is then divided into smaller parts, called functional elements, which describe what each part needs to realize. However, the intention of the design or solution is not included yet. Nowadays, in regards to the Industry 4.0, new methods and tools to manufacture products are used in companies such as additive manufacturing. This process allows the production of complex products and enables to generate meta-structures (lattice or skeleton) directly from functional elements. Besides, it opens up new opportunities for innovative and high-performance products, but this technology implies considering new manufacturing constraints as early as possible in the design phase. Moreover, complex geometries can hardly be represented using papers and 2D drawings. 3D sketches and sculpting are required to quickly create and visualize what students have in mind [2]

Today, it is often observed that additive manufacturing offers many possibilities and degrees of freedom to production engineering, which design technicians/engineers are not aware. They therefore do not use full potential and industrial needs cannot be filled. AM generative methods and the interaction of the individual part of a system are associated to functionalities. However, in-depth understanding of how the systems work and the tools used is precisely what is needed in the area of additive manufacturing. They can develop the right approach to design up to the relevant production task. This paper hence describes a method for teaching about "design for AM". Design and practical use are also taught. They need experiments to critically evaluate designs using those new technology. The aim of this is to give students practical design skills and teach them about options offer by AM at part and product level. First, a literature review about teaching methods and design for AM is presented. Second, teaching sequences and tools are described. Third, a case study is presented and discussed.

2 Literature review

2.1 Active pedagogical guidelines

Problem-based learning

Problem-Based Learning (PBL) is a student-driven pedagogy. Students learn about a topic through experience. Complex real-world problems are used. They solve an open-ended problem related [3]. It promotes student learning of concepts and principles. The PBL process does not focus on problem solving, but allows active development of other skills and attributes. Knowledge acquisition, enhanced group collaboration and communication are skills that can be gained [4]. It was applied in a context of our industry Design for Additive Manufacturing courses.

Data-driven learning

Data-Driven Learning (DDL) has been recognized as one of the most important aspects of content and value generation in the 21st century. DDL is a good practice to align theories and practices. Learners observe patterns, meanings or other aspects through data analysis. DDL changes learning environment where teacher is no longer the only authoritative owner of knowledge, but rather a "consultant". Additive manufacturing is associated into 4.0 industry. Complex data and its analysis can contribute to geometry/process/material interaction.

2.2 Additive manufacturing process

The AM technology has changed expert practice, and the knowledge and know-how related to this process are still evolving with the processx. AM experts use various strategies to design or manufacture parts precisely but the knowledge of how the process occurs is not well understood or formalized. Gibson et al. [5] see many steps in the CAD-to-Part lifecycle which start from STL formats, part removal, clean-up and post-processing. AM is seen as a long process. It starts from the design phase (part geometry and optimization) up to the quality control of the final part. They are all in interaction For instance, support removal, "depowdering" or post processing are activities that have to be considered because it is time consuming. However, there is also a step of preparation that clusters design phase. This event needs to be considered as early as possible. That's why a novel approach to aid students during the conceptual design has been developed, tested with French engineering students and will be presented in this paper. The objective is to use serious-game and immersive tools to increase the interaction, immersion and imagination. Three game steps are defined and related to the students' skill level.

2.3 Immersive tool for teaching

The three properties of Immersive Tools (IMT) (virtual reality or augmented reality) are expressed by Burdea and Coiffet [6] as the “3 I’s”: Immersion, Interaction and Imagination. That definition well sums up the interest of this technology. For instance, the user can be fully immersed into a specific environment (as if it existed) without physically creating it. Moreover, the user can directly interact with his environment and can thus detect and solve issues more easily or more quickly. IMT is also quite close to the real world and hence do not prevent human imagination. IMT has first appeared in the gaming domain, but is currently used in various domains, such as surgical [7], anatomy [8], music teaching [9] and so on. The technology is also widely used in the domain of engineering and training. Main research works focus on the validation of the design. Halabi [10] uses IMT in digital prototyping to evaluate the design of his students. Abulrub [11] makes project reviews with IMT and Castronovo [12] detect mistakes and review students’ skills in the form of a game in construction projects. Wolfartsberger [13] uses IMT to easily assemble and disassemble parts from a product during a project review. That enables every project stakeholder to participate in the meeting even if they are unfamiliar with CAD softwares. In the training domain, IMT is integrated to engineering students’ course through projects (e.g. in Karlsruhe Institute of Technology in Germany). These projects enable them to enhance their IMT knowledge and re-use them on future projects [14].IMT has many advantages:

- Enhance students’ motivation and creativity [6];
- Prepare students to the Industry 4.0: acquaintance to IMT [4]
- Improve communication and interactions among a group of students [13]
- Explain complex, theoretical and hidden concepts [15]
- Train in a real environment at scale one [4]

Besides, IMT is also used to realize 3D sketches. Study has been pursued to evaluate the impact of IMT on early design stages, and concept generation has been improved with the use of these tools [16]. In sketch-based modelling, Wang et al. [17] have developed algorithm to reconstruct surfaces of 3D models. Besides, De Klerk et al. [18] have made an IMT environment to explore and quickly create simplified models at different scales in the early design stages. The authors mention that a CAD software is unnecessary at this stage, as required precision is not so high. Interactive 3D model reconstruction has also been developed so that designers can evaluate in a short amount of time the potential of numerous design variations [20]

3 DfAM courses

3.1 Structure

The presented organization is setting up at Bordeaux University (in France) for third year bachelor’s degree students in Mechanical Design and Production. The objective of the whole course is to teach to students the link between product / process / material. Concerning their background, they have solid knowledge on advanced design, such as surface generation and parametric design, and they have followed an initiation to the additive manufacturing process. The development was guided by the need for industry 4.0. New technician will develop new product using advanced manufacturing technology so it is stated an importance of linking design and AM. Students can :

- Specify capabilities, limitations of AM technologies
- Quantify and select AM technologies for specific design-manufacturing applications
- Define causes of errors and irregularities
- Apply DfAM for an innovative challenging design and manufacturing application.

These objectives are synthetization and knowledge of AM. Instructors provide a high-level introduction to AM technologies. Functional classification framework is used to provide possibilities and limits based on benchmark analysis [18]. Case studies and commercial applications are used for motivation with an industrial context. Different elements are presented:

- Identifying Opportunities: identify AM product development opportunities and customer needs.
- AM Project Planning and Economics: impact of the digital manufacturing paradigm.
- AM Concept Generation: customization, low-volume production, assembly reduction, and complex geometry.
- AM Embodiment Design: structure and topological optimization + AM tolerancing considerations for various part features (e.g., through holes, snap-fits, living hinges, etc.)
- AM Detailed Design: AM common build strategies (and potential errors) caused by part orientation, poor interlayer bonding, and resolution limitations

Then, active pedagogical methods are used in three steps (cf. Figure 1): Benchmarking Part, Dissection/Selection and Design Problem. This course has been conceived as a learning game to motivate 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 roughness, the properties? The second module (B) allows to evaluate design rules based on 3D printed part with functional dimensioning and tolerancing (FD&T). The idea is to highlight causal effect, which ensures all requirements link to specific manufacturing constraints. And finally, the third module (C) introduces a 3D sketch approach as a competition between teams. DfAM is then explored creating a new product that is suitable for AM only.

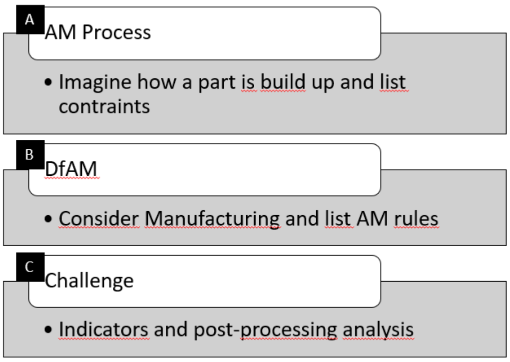


Fig. 1. Course configuration

3.2 STEP A

A global approach, Design For Manufacturing (DFM) encompasses a set of activities such as: the choice of processes, the choice of materials and the evaluation of the manufacturability of a product. This approach is linked to factors that influence the decision-making process. The paper [19] classified AM benchmarking into three types: (i) geometric, (ii) mechanical, and (iii) process benchmark. It is used to measure the geometric features of a part (i.e. tolerances, accuracy, repeatability and surface finish). It is used to analyze the mechanical properties to establish with process related parameters [20] Finally AM has lack of precision and poor dimensional accuracy so a process benchmark is required [21]. Precision and accuracy are critical to the fundamental layering mechanism and require some of the error correction methods. There are in this case different immersive tool examples providing information about the process such as layer size, hot-end temperature, acceleration-deceleration effects (Figure 2). It helps to understand cause and effect in the process and associated to benchmark features.

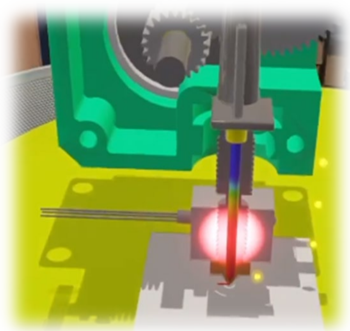


Fig. 2. Modelling hot-end temperature of FDM process

The first PBL activity of the course is focused on capabilities and limitations of AM technologies. Students actively explore AM consideration by measuring features on a benchmark one of the three metrics: resolution, accuracy, or surface finish. A castle inspired from Vauban's architecture is used. A branch is composed of six zones dedicated to the generation of a basic geometric model and requirements to test the accuracy and repeatability (Figure 3). The fabricated benchmark artifact is easily measurable using a 3D scanner or a coordinate measuring machine. The designed artifact, e.g., should be large enough to test the performance near the edges as well as near the center. Substantial number features are integrated in the model, as well as holes, pockets, and bosses, and almost all the other features mentioned in previous section.

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

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

The part enables students to observe the effects of potential sources of AM build errors (e.g., printers, materials, layer thickness, etc.) on the chosen metric FD&T. The factors related to the characteristics of the product join the possibilities of shaping the product which influence manufacturability. Finally, students prepare a "pitch" on four letters that have geometric features to show their knowledge on AM possibilities. The students will mark the other teams on five points.

3.3 STEP B

The definition of the shape of the product is closely linked to the choice of AM processes in interaction with the identified material. Thus, many criteria and design rules will influence the functionality and quality of the product. It is in the mastery of the simultaneous processing of several interconnected criteria, in an integrated design approach, that DFAM resides. The use of 3D printing technologies requires good design and manufacturing practices that must be assimilated very early in order to be considered at the product definition stage. The aim is also to minimize the difficulties and the manufacturing costs. The skills acquired through this step are:

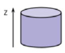
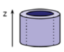
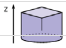
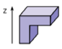
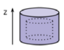
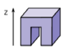
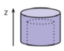
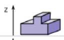
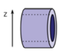
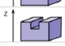
- To understand the implication of Additive Manufacturing processes and materials in the process of defining and designing a product
- To manage several technological criteria simultaneously in order to control the design, quality and manufacturing costs
- To optimize the management of a design project for AM through the DFAM method

At this step, students imagine what can be done but they only oversee the problem. An introduction time is then proposed about placement on a building platform and simple shape examples are discussed for interaction and imagination reaction. Immersion is given by the “architect features” cards. They have cards about causes and need to discuss about consequences in terms of process, cost, properties etc… This introduction uses immersive tools to obtain 3D representation of build platform mechanisms. They need to have understood the eight rules [23]:

- Part silhouette
- Overhangs
- Think about deformation risks
- Overall part size/ Nesting density
- Holes or thread forms
- Surface finish and references
- Support removal

Afterwards, an activity is proposed to generate data for DDL. The idea is to give 3D printed parts made with three technologies (Fused Filament Fiber, Direct Light Projection and Laser Powder Bed Fusion) with the same orientation of build-up. First, they classify defects (observed with eyes) in the build-up direction. This operation could also be developed with metrology tool or in-situ diagnostic. Second, they list features. They refer to a previous benchmark analysis work (Table 1). Each group has three objects analyzed and their development are shared.

Table 1. Pattern development (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			

An initial discussion is launched about AM rules development with an example. Students try to generate relationships between a patterns and a defects library. They define AM rules with standardization map. The objective is to complete a table of AM rules. For example, they can locate a defect within two branches with a half-sphere shape. It occurs before the merging with the branches. They can associate the defect to "bridge". This corresponds to a rule of overlap limits. It illustrates the collapsing of a surface and the idea to optimize using “Gothic” arches for instance. Students have data on the capabilities of leading AM process/material for different patterns and organize it into a table that offers side-by-side comparisons of the alternatives. They present three AM rules (group by group) and they win a point if it is justified. A discussion is proposed with the other groups. Whenever necessary, assistance is provided to refine their understanding with specific manufactured part using the three technologies.

Knowledge of manufacturing processes and materials are applied to identify the most likely health-material and geometry association. Many students find this task difficult than expected. It requires considerable knowledge of AM processes. Multi-scale cause can contribute to specific defects, microstructure or deviations. Strengths and capabilities and a sophisticated reasoning about the most likely fabrication path is difficult and need experience.

3.4 STEP C

During previous steps, attendees are exposed to factors that affect the print quality and economic viability. The theoretical topics covered are ordered to make a problem-based exercises. The first part of the curriculum covers some of the theoretical aspects and design rules of printing. Then, they do a design exercise about a block manifold into an AM specication. The block manifold is a block of metal with holes drilled into it and its functionality is to allow hydraulic fluid to go from a source to several destinations. The requirements can concern technical, weight or functional. The students start with an idea and draw with the 3D sketch tool. The first concept considers only input/output localization and general space definition. They answer to the requirements considering the process constraints. One objective asked in PBL is minimize weight (Figure 4). The attendees are first shown removing unrequired material from the block manifold, through a simple ‘shell’ operation, would result in. The result is a ‘minimal’ set of pipes. Functional surfaces are defined and a global overview of DfAM is discussed. Finally, the objective is to make the manifold as light as possible but, it needs to be manufacturable with as little post-processing labor. Figure 3 shows an example after shell tool use, redesign cylinder with fixture supports and overhang analysis. Different tools are proposed and DfAM steps are driven.

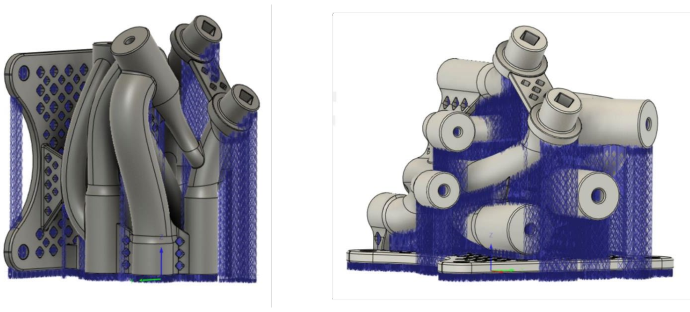


Fig. 4. Two orientation analysis with support structure

The team starts to finalize design ideas. The first thing is to discuss the print orientation for the manifold based on functional surfaces and post-machining. They conclude that it contributes function and complexity operation. Whenever they are not sure, they are encouraged to save their work in STL format. They are asked to present their idea with arguments to an expert. They can also visualize with the AM software the support material and indicators such as proximity or thickness for their current design. This teaches them the importance of being able to quickly switch back and forth between the different tool applications. It is required for different aspects AM (numerical twin development). They can for instance have sensibility analysis of thin wall or thin gap which contributes to bad printing in metallic part. After that, the part is saved into OBJ format and use an IMT to evaluate post-processing. This immersive time is interesting to imagine hand operation required and avoid inaccessible zones to remove support or finishing operation (Figure 5). Students can also criticize support structure depending on support removal forces that will be applied.

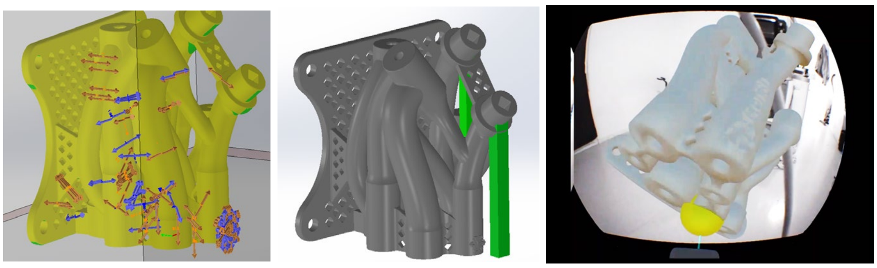


Fig. 5. Thin wall, thin gap, overhang analysis to optimized manufacturability and support removal through IMT integration

Finally, each team pitches and is evaluated by other teams. The idea is that students must be critical about a concept by arguing about the advantages and disadvantages of other ideas. The team then needs to propose a solution according to the comments. Design strategies is surprisingly varied, but they are mostly successful. There is not a single correct way of designing for AM but they all can justify with quantitative information and iteration. There are many different solutions, each of which has different implications on the quality and function of the part. Once the attendees have finished their designs, they are purposefully not corrected, as these faults will help to promote further learning. Learning experience is driven for instance with the difficulty to remove support material. This truly is an eye-opener as, upon attempting to remove support. They immediately grasp why it is so important. It is worthy to check post AM operation. Also, geometric deviation or defects can be observed. It can be so hard to remove and therefore add costs implication to the part. This hands-on experience is probably the element that can reach DfAM usefulness in a significant way.

4 DIFFICULTIES AND VALIDATION OF THE PROPOSED APPROACH

The significant change in the designs that novices produced from step A to step B is drastic. Theoretical knowledge using active pedagogical strategy was worthy. However, it gives us an idea to increase this development for specific AM processes. A significant decrease in poor designs is noticed. The presentation of new concepts seems beneficial. One key aspect of this study was that the designs were evaluated and criticized by the students themselves. This effectively forced novices to evaluate their designs and iterate when they were not good enough.

In the second validation step, no differences were seen with data study and the group that did not manage to overcome AM rules. This result was expressed by students as 'time consuming'. They admit formalization rules is hard and they prefer transmissive interaction in this case. However, very interesting questions and remarks were developed in this session. Time for note making is required or a feedback document should be proposed. Nevertheless, the extracted information highlights the need for a "re-design" of the considered first attempt based on AM experience. As presented by Carfagni et al. (2020), actual roles of prototypes in design processes is very important. The step C enabled the students to work with DFAM thinking in order to allow students to better exploit the potentialities of AM. However, the problem appears to be quite complex because the students had no experience with the different technologies. There is the need of additional data to comprehensively develop successful academic programs. All students wanted to experiment process. Part examples were not enough and they mixed their design method with conventional tools. Accordingly, besides the need of additional information for AM purposes, experiment highlights that results from different technological backgrounds can be very different or even conflicting with each other. They do not design if they have to use different technology and they have difficulties to obtain general survey.

Finally, the challenge of the step C changed everything. The possibilities to check their design and 3D visualization help them to mostly find ways for manufacturability. This leads to believe that students propose almost perfect designs. However, references for post-processing or residual stresses evaluation should be included. They express a good feedback to have 3D models with simple operations to generate functional surfaces and support structures. The teacher should be aware that from scratch it is almost impossible. A guide is necessary and CAD skills should not act.

5 CONCLUSION AND PERSPECTIVES

This paper has presented a novel approach to integrate additive manufacturing constraints in the conceptual design phase. Game approaches enable interaction and team work. The objective was an awareness of cross-disciplinary around additive manufacturing. Design driven by manufacturing factors simultaneously considers design goals and manufacturing constraints to identify manufacturing issues and facilitate their resolution during design. During the course, the students received insights on the following topics: From the concept, design, data preparation, and post-processing using IMT, the students experienced the whole AM process chain. The systematical approach of the course led the students through the team project where they received expert feedback and real-life experiences from various prototypes. By applying PB and DDL, students successfully developed skills which are important for engineers, especially in the field of product. They can be applied to different students and adapted to skill levels. They have been tested for two years now and are still in development. The key words were to place the right material at the right place for the best reasons and they got it.

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