

Teaching Design for Additive Manufacturing Through Problem-Based Learning



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1 Problem-Based Learning

From various definitions of problem based learning (PBL) we find that it is most commonly defined as a student-driven pedagogy in which students learn about a subject through the experience of solving an open-ended problem related to certain trigger material (Barell 2006; Aalborg 2015). Complex real-world problems are used as a vehicle to promote student learning of concepts and principles, as opposed to the more traditional direct presentation of facts and concepts through classroom lectures. The PBL process does not focus just on problem solving with a defined solution, but rather allows for the development of other desirable skills and attributes. These, in particular, include knowledge acquisition, enhanced group collaboration and communication (Peters et al. 2006). Though it sounds like a cliché it, effectively, encourages students to learn how to learn. The PBL learning process involves working in small groups of students, where each student takes on a specific role within the group that may be sometimes formal and sometimes informal (and the role often rotates from project to project). It is focused on the students building their own learning from reflection and reasoning (Aalborg 2015).

In PBL, the role of the teacher is to facilitate learning by supporting, guiding, and monitoring the learning process. The teacher must build student confidence to take on the problem, and encourage the students, while also stretching their understanding. This process is based on constructivism (Zemesukis Education 2017). In PBL it is also often up to the student to determine what they need to be taught, and for the teacher to then deliver that particular required knowledge in the most appropriate way.

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Some of the typical characteristics of good PBL problems include (Duch et al. 2001):

- The problem must motivate students to seek out a deeper understanding of concepts.
- The problem should require students to make reasoned decisions and to defend them.
- The problem should incorporate the content objectives in such a way as to connect it to previous courses/knowledge.
- If used for a group project, the problem needs a level of complexity to ensure that the students must work together to solve it.
- If used for a multistage project, the initial steps of the problem should be open-ended and engaging to draw students into the problem.

Learning some theory about PBL was all well and good, but the challenge was how teachers at Lund University could apply it in the particular context of our industry DfAM courses at Lund University. Upon looking at how other universities have been applying PBL, we find a very wide spectrum of application. Some universities do not use PBL at all, and rather rely on courses that are mainly based on traditional classroom lectures. Other universities, such as Aalborg University in Denmark, are at the other extreme in which almost the entire course is focused on PBL (Aalborg 2015). In the case of Lund University, the decision was made to use a hybrid model in which half the course was delivered using a standard class-room approach, and the other half was delivered using problem-based learning.

2 Design for Additive Manufacturing

Design for additive manufacturing (DfAM) is about the particular design techniques that need to be developed in order to maximize the potential benefits of additive manufacturing. Part production using AM brings both benefits and challenges to engineers and designers. Parts can be made with great complexity, and process considerations are less prominent and very different to those of conventional manufacturing. Designers also have the opportunity to create more design variations, and specific parts in a product can be tailored to markets around the world, different target customer groups, or even to individual customers. A product can, for example, have standard internal parts, produced through conventional manufacturing, and a customer-specific external shape made by AM (Wohlers et al. 2017).

Although AM removes many of the constraints of conventional manufacturing, it imposes some new constraints of its own. When designing for AM, designers therefore need to change their approach and learn new design techniques suited to AM. In the past, design for manufacturing guidelines and rules dictated that part shapes should be kept as simple as possible. Detailed consideration would be given to manufacturing process requirements such as parting lines, draft angles, and wall thicknesses. Many designers have been educated and trained with this view, which

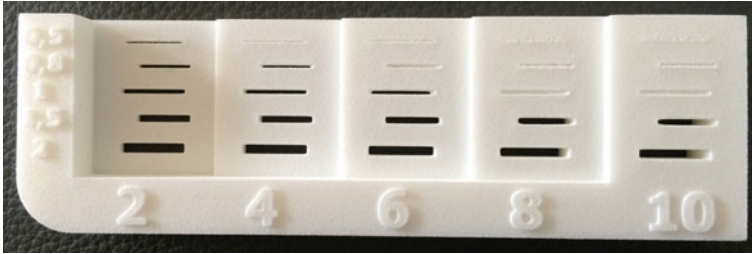


Fig. 1 DfAM guideline example of the minimum allowable hole size dependency on wall thickness

underpins everything they have learned. Designing for AM brings radical change that requires a new way of thinking among designers. With proper understanding and experience, designers can improve product functionality by using a number of new techniques (Wohlers et al. 2017).

New design techniques that are particular to AM include, for example, topology optimization and lattice structures as tools to produce lightweight parts. Part consolidation is a technique that allows many simple parts to be combined into one much more complex part, which would be a challenge for conventional manufacturing but isn't for AM. Special techniques around mass-customization and conformal cooling strategies can also be used to add value to products. Many design guidelines governing elements such as wall thicknesses, hole sizes, pin sizes, etc. have been developed but, in the world of AM, engineers and designers must learn to see these only as general guidelines, rather than as strict design rules that can be applied in any situation.

One of the other difficulties of AM is that most of the design-guidelines depend on a number of parameters that affect part quality. Minimum allowable hole size through a wall, for example, is dependent on the wall thickness the hole is going through (Fig. 1).

Print orientation, for example, plays a role on the anisotropy of the part, the surface quality of the part, and how much support material it requires. So changing the print orientation of the part affects how much support material will be required. Support material, however, is also related to the angle of any unsupported features of the part, and it's need is also related to the residual stress in the part. So if a part, for example, has uneven thicknesses of material, it may contain greater residual stress, so may require extra support material to compensate for that. The above are just a few examples of some of the complexities involved in DfAM (Fig. 2).



Fig. 2 Overview of some of the DfAM guidelines

3 The Application of PBL for Industry DfAM Courses at Lund University

Since 2015, Lund University has been offering a number of external industry based courses to educate engineers and designers about additive manufacturing. For all these courses Lund University has employed a PBL teaching approach in which about half the course is focused around practical hands-on problems in which the attendees can apply the theoretical learning from the other half of the course. The courses are given over four full days, divided into two sets of two days, and contain approximately the same amount of material that would be given in a full semester undergraduate course. The reason these courses are so concentrated, fast paced, and packed full of information is that it can be difficult for company employees to take more than a few days off at once. The curriculum of material covered in these courses includes (Table 1).

During the course, attendees are exposed to the majority of factors that affect the print quality and economic viability of an AM part. The theoretical topics covered are, more or less, ordered in a way to make the topics as relevant as possible to the problem-based exercises that follow. As an example of the application of PBL, in the first part of the curriculum, the course covers some of the theoretical aspects and design rules of printing in metal. In particular, it discusses the fact that the support material that is required by metal AM systems to anchor the part to the build plate, and to help with heat-transfer to minimize distortion, and to resist the mechanical force of the powder spreading mechanism can make metal printing a difficult challenge. A point that is emphasized during the theory sessions is that this support material can play a major role on part cost, as it can require substantial labor to remove.

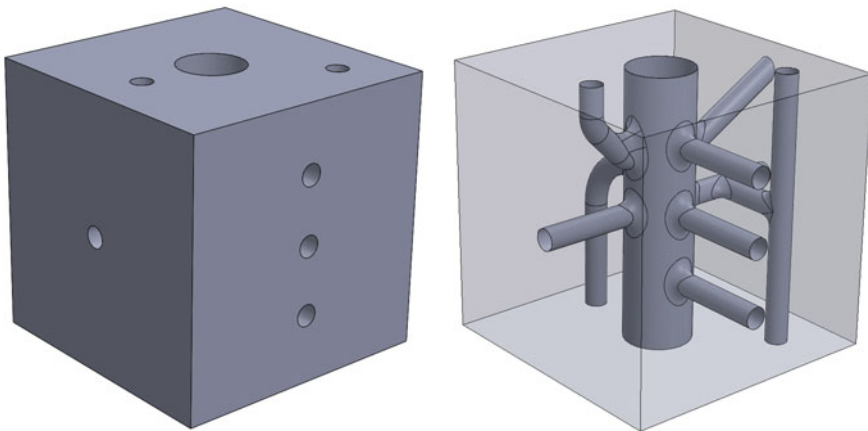
Table 1 Sample curriculum for four-day design for AM course

Legend	Theory session	Hands-on session
Topic	Details	
<i>Day 1</i>		
Intro to AM. The state of the AM industry	Recent AM growth trends and developments around the world. Benefits of AM in the context of DfAM, how AM is being applied, and how certain parts can be designed for AM	
AM process: from CAD to part	Examining the complete AM process chain, from CAD part creation, to part production. Attendees will gain an understanding of the entire process chain and how it helps them to design better AM parts, file formats, and working with STL manipulation software such as Magics. The session also covers the main AM technologies, with advantages/disadvantages/applications of each	
Lattice structure exercise	An exercise in which a solid part is transformed into a shell filled with a lattice structure. Several different lattice strategies are explored and tested	
Part consolidation exercise	Implications of part consolidation for AM. Hands-on exercises in part consolidation	
<i>Day 2</i>		
AM process: from CAD to part	Continuation of Day 1 session: Description of other popular AM technologies	
Designing for metal AM.	Specific issues and guidelines around designing for metal AM, including anisotropy, process constraints, general guidelines related to wall thicknesses, hole sizes, tolerances, angles, etc. The session also covers how AM metal powders are made, and what their effect is on the metallurgical properties of parts.	
Topology optimization	Session on designing topology-optimized parts for additive manufacturing, and creating lightweight parts using software such as Inspire from SolidThinking. The general workflow of topology optimization, setting up multiple load-cases and then using the generated ideas to produce a combined design	
AM Design optimisation exercise	The thought processes behind design for AM In this exercise we design a hydraulic manifold while keeping print orientation and support material in mind	
<i>Day 3</i>		
Support material removal and lab visit	Visit of AM facility. Removal of metal support material from attendee parts printed over break	
Designing for metal AM part 2	Continuation of day 2 session on designing for metal AM. Close look at metal AM post-processing and material properties. Examination of health and safety aspects of working with metal powders. Implications around certification of metal AM parts	
Panel session	Group of experts discuss lessons learned with AM, problems, challenges, opportunities, and design considerations	
Design for mass-customization exercise	Hands-on exercise to design a custom product using a combination of CAD, 3D scanning, and STL editing software. This exercise introduces attendees to the idea of working with multiple software packages and technologies to produce parts that are optimized for AM	

(continued)

Table 1 (continued)

Legend	Theory session	Hands-on session
Topic	Details	
<i>Day 4</i>		
Designing for other AM processes	Specific issues and design guidelines surrounding polymer AM (FDM, LS, SL, etc.), including post-processing, etc.	
Tooling applications of AM	Looking at AM beyond direct part production: Injection-molding tools, sheet-metal forming tools, extrusion tools, jigs and fixtures, etc. Adding mounting fixtures to parts to ease mounting on CNC machines for more efficient post-processing	
Economics of AM	An examination of the factors that affect AM part cost and economic models on how to deal with them	
AM as an innovation catalyst	Using AM, and other technologies, as a tool to change how we think about products, and can use them to stimulate innovation	
Putting it all together	Hands-on exercise to design a product that can be printed in metal, using the learning from the last 4 days, and with minimal support material and post processing	
AM in the near future	Looking at where AM and design software tools are headed in the near future and the implications they will have on DfAM	

**Fig. 3** Simplified block design manifold showing only the required in and out channels

Later that session, course attendees undertake a hands-on design exercise in which they are asked to redesign a block manifold into one that is designed for AM. The block manifold is, literally, what it sounds like: a block of steel with holes drilled into it to allow hydraulic fluid to go from a source to several destinations. Block manifolds are used in many industrial applications where fluid needs to be delivered from one source to multiple recipients. Their weight, however, can be considerable so any weight reduction that could potentially be achieved through the use of AM represents great benefits to any products that benefit from being lighter (Fig. 3).

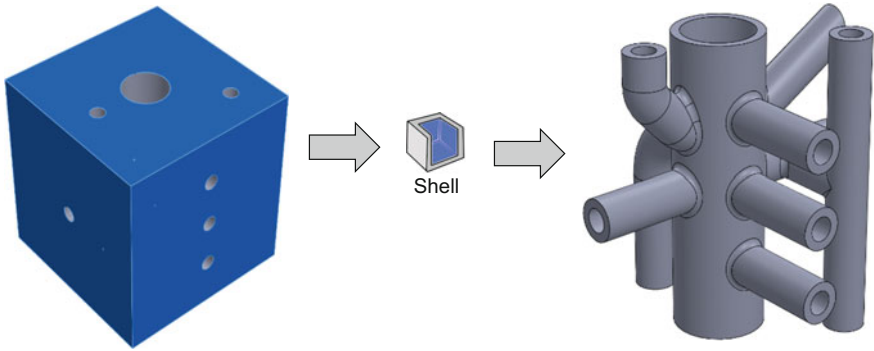


Fig. 4 Manifold design before and after shell operation on block design

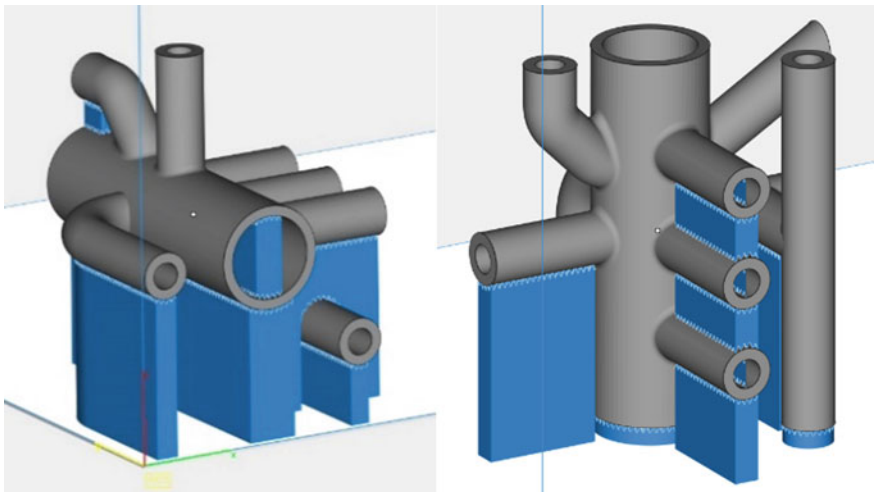


Fig. 5 Support material required by shelled block design in two different print orientations

The attendees are first shown what simply removing all the unrequired material from the block manifold, through a simple ‘shell’ operation, would result in. The result is a ‘minimal’ set of pipes that are connected together as follows (Fig. 4).

The attendees are then shown, in software, what the results would be, from a support material point of view, if the part was printed as is. This is important, as it is often the attendees first exposure to automated support material generation software (Fig. 5).

From this point, the attendees are split into teams of 3 or 4 members to redesign the manifold into a new design that minimizes the amount of support material used. The objective is to make the manifold as light as possible but, at the same time, to make it manufacturable with as little post-processing labor as possible. To, purposefully,

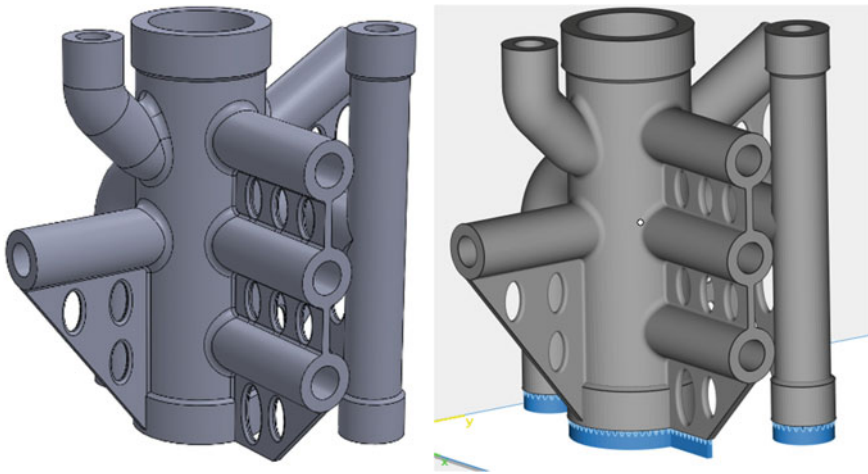


Fig. 6 Example of a design that requires minimal support material

increase the level of difficulty of the task, the attendees are told that they cannot move any of the positions of the outside connection points of the manifold.

The attendees select a member of their team to be the CAD operator, and they use whatever CAD program they are most comfortable with. Another team member is designated as the AM machine operator, who will set up that CAD models in the AM software and generate its support material. The entire team now starts to generate design ideas, using the knowledge gained during the previous theory sessions, and the CAD operator implements those into a new design. The first thing they typically first discuss is the best print orientation for the manifold, and run through the effects on the manifold of different print orientations. Whenever they are not sure of the effect of one of their decisions, they are encouraged to save their work in STL format (the de facto file format for AM) and the designated machine operator then uses the AM software to generate the support material for their current design. This teaches them the importance of being able to quickly switch back and forth between the different software applications that may be required for different aspects of AM (Fig. 6).

The design session takes about 2 h, at the end of which all the teams have generally completed a design that uses relatively little support material. The number of design strategies used by different groups is surprisingly varied, but they are also mostly successful. This is useful in demonstrating to the students that there is no single correct way of designing for AM. 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, if the teacher sees faults in the designs that will require the use of support material, these are purposefully not corrected, as these faults will help to promote further learning. To further enhance the learning experience, and to truly drive home the difficulty that support material can impart to metal AM, during

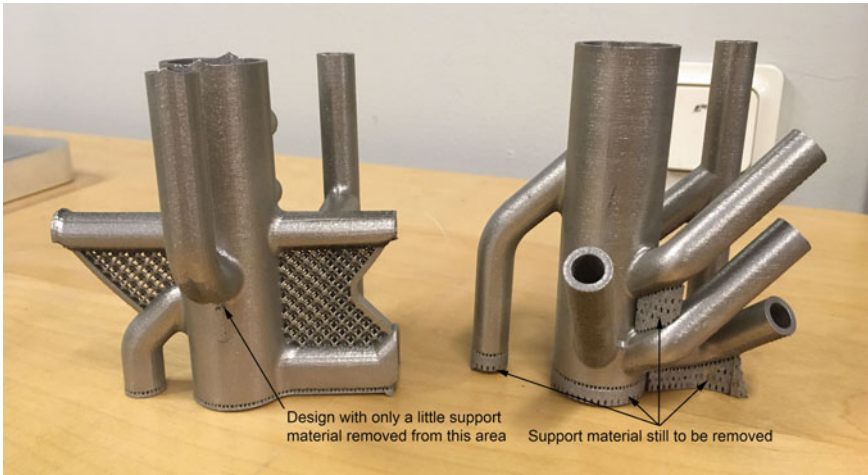


Fig. 7 Examples of a course attendee manifold designs

the break between the first two days of the course and the second two days of the course, the attendees designs are printed in metal.

The first session after the break between the two parts of the course includes a visit to a local AM lab, so the attendees can see AM machines in action, and also includes a hands-on session where the attendees have to remove the support material from the manifold parts they designed before the break. This truly is an eye-opener as, upon attempting to remove support material themselves, the attendees immediately grasp why it is so important to try and design to minimize support, because it can be so hard to remove and therefore adds such a lot of labor costs to the part. This hands-on experience is probably one of the highlights of the course in terms of really driving home the learning in a significant way. Once a person has personally experienced the challenges of metal AM support material removal, they truly understand one of the many goals of DfAM (Fig. 7).

4 Conclusions

Additive manufacturing is an applied teaching area in that just teaching the theory of AM holds relatively little meaning to those being taught. You can teach them what can be done with AM, but to teach them the intricacies of the design rules, many of which depend on a great number of factors, such as print orientation, material, angles, etc. the best way is to get them to solve a real-world problem by designing a part, and printing it themselves so they can truly understand the results of their thought process, be it successful or unsuccessful. Because of this, teaching design for additive manufacturing is well suited to problem-based learning

In the DfAM industry courses offered by Lund University, the response by attendees to this problem-based teaching approach has been phenomenal, and because of this, the courses have received excellent reviews. Staff at Lund University believe this is because, when the attendees are given real-world problems to solve, they work as teams to resolve them and, whether their solution to the problem is successful or not, the learning they get from it, either way, is far greater than what they get from just memorizing course material.

Though the problem based teaching approach described in this chapter was developed by staff at Lund University, in Sweden, the DfAM courses have been offered to companies all over Europe, the United States, and Australasia, which demonstrates that the approach is applicable to any university, or organization, in any country. Several courses within the Lund University School of Engineering undergraduate program have now being adapted to employ this same teaching approach with great success.

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Professor Olaf Diegel is both an educator and a practitioner of product development with an excellent track record of developing innovative solutions to engineering problems. In his role as professor of product development, in the department of design sciences of the faculty of engineering at Lund University, in Sweden, he is heavily involved in all aspects of product development and is widely published in the areas of additive manufacturing and rapid product development. In his consulting practice he develops a wide range of products for companies around the world. Over the past 10 years he has developed over 100 commercialized new products including innovative new theatre lighting products, security and marine products and several home health monitoring products and, for this work, has received numerous product development awards. Over the last 20 years, Olaf has become a passionate follower of 3D printing (additive manufacturing). He believes it is one of the technologies that has been a real godsend to innovation as it allows designers and inventors to instantly test out ideas to see if they work. It also removes the traditional manufacturing constraints that have become a barrier to creativity, and allows us to get real products to market without the normally high costs that can become a barrier to innovation.

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External Resources: Swedish Additive Manufacturing Association supports activities that will ensure Swedish industries are competitive and leading through high-value manufacturing to create growth, uniqueness, jobs, and export opportunities. <http://www.sveat.se>.