Getting Chemical and Biochemical Engineers Excited about Additive Manufacturing

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A new course was designed to attract chemical and bioengineers to additive manufacturing and to provide them with an effective approach to this new field. The goal is a wider use of the advantages of additive manufacturing for complex multi-functional components in chemical process engineering. We describe the structure of the course and the experiences from the first two years. Students show great interest and are able to develop their own functional components with assistance. Yet many have deficits in the use of CAD software, which will be remedied in the future through a specific lecture.

1 Additive Manufacturing in Process Engineering

Triggered first of all by an amazing increase of performance in digital computing and laser technology, additive manufacturing (AM), also known as 3D printing, has evolved over the past two decades from a curiosity for niche applications to an important part of the manufacturing industry with a growing number of serious applications in many sectors [1–4]. One of the revolutionary aspects of AM is a very low entry hurdle given the availability of low-cost 3D printers and the fact that even people with little experience in classical manufacturing can now develop and produce complex parts at home on their own or collectively by collaboration in networks. This has supported the emergence of an active and creative maker community. The maker culture is a contemporary subculture, which represents a technology-based extension of do-it-yourself culture overlapping with hardware-oriented parts of hacker culture. Makers reveal themselves both in the creation of new devices and in the tinkering with existing ones [5]. Whilst most of this activity so far can be classified as part of the wider field of mechanical engineering, the core ideas increasingly fall on fertile ground also with chemical and bioengineers.

Process intensification through miniaturization of flow ducts in apparatuses, modularization of chemical plants building on standardized process equipment, and the transition from classical batch operations to automated continuous operation are key aspects of micro process technology and flow chemistry, both supporting the concept of modular plants [6]. This is applicable first of all to the production of specialty chemicals and active pharmaceutical ingredients. In this area shorter time to market and the ability to

customize production are competitive advantages and frequent product changes call for plant reconfigurability and the ability to reuse existing process equipment assemblies to improve the economics. Decentralized power-to-X plants for turning local excess of renewable electrical energy together with CO_2, H_2O or N_2 into easily storable chemical energy carriers mark another application area where flexible and agile modular plants based on high-performing but cost-effective standardized process equipment are needed. Whilst a wealth of advanced designs for intensified mixers, heat exchangers, chemical reactors, separation units and multifunctional process devices have already been developed using classical micro fabrication approaches, AM now adds new opportunities to provide solutions given the unique possibility of fast and seamless transition from a computer-based design to its physical realization [2]. Yet the young process engineers are often not aware of these opportunities, and therefore the future application of this technology in chemical and bioengineering would be restricted.

As an answer to this need, we have developed and taught a new course at KIT, which sets out to introduce the

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concept and the potential of AM to the students in chemical and biochemical process engineering. More specifically, the goals of this course are:

– to make the students aware of and familiar with the opportunities of AM for process engineering,
– to show them that AM is a completely new approach enabling structures not possible otherwise,
– to foster the student's digital skills,
– to make them familiar with some of the most important AM methods – material extrusion and vat polymerization for 3D printing of plastics, laser-beam powder bed fusion for metals, and binder jetting for metals and ceramics able to make dense as well as porous parts,
– to convey to them the concept of fully digital fabrication chain using and linking together modeling and simulation, computer-aided design and additive fabrication (cf. Fig. 2),
– to show them exciting AM examples from research,
– to give them the opportunity to work with an industry-type professional 3D printer, and
– to prepare them for a second encounter with AM, be it in academic research or industry.

A practical training makes part of the module. In the practical, the students acquire hands on experience with the use of a metal 3D printer for fabrication of highly precise parts with complex shape. For this, we provide access to a recently established dedicated AM lab (cf. Fig. 1) where we integrate the experience of several decades of work on the development, characterization and application of advanced microstructured process units.

2 From Design to Experimental Testing in One Course

Additive manufacturing has been included in a wide range of engineering education [7]. The content of such courses often is tailored to the expertise and job description of the audience. The range of educational needs is very heterogeneous in vocational education and training for the existing workforce. Machine operators often are already certified mechanics and require a dedicated introduction in an AM process and machine type while engineers in the design department require a broader overview on the AM processes, their capabilities and restriction. There are a number programs offered by industry and professional associations, e.g., VDI [8], DVS [9] and SwissMEM [10], and technology transfer institutions, e.g., Fraunhofer [11] and inspire [12]. Most of these courses combine theoretical inputs and practical applications to transfer knowledge and build up experience. The Experience Transfer Model (ETM) [13] is a framework for teaching design for AM knowledge to professionals. It enables participants to select suitable parts and to redesign it for additive manufacturing.

Academic education for engineers at universities is different in terms of audience and scope compared to training experienced professionals from industry. The audience is more homogeneous since most students are at a similar stage in their academic education. This makes the formal teaching more efficient because the curriculum can build on a common starting point while the informal learning between students lacks the variety of expertise from different industrial backgrounds. The lecturer needs to compensate the informal learning by providing more examples and case studies from industry. The scope of the lecture is related to the field of study of the audience and typical job profiles of engineers in this field. Nevertheless, the curriculum should be broad since the career paths of the students are not determined yet and job profiles are becoming more flexible and fluent.

Didactic concepts like problem-based learning or the experience transfer model are typical approaches to build up AM competencies through a combination of lecture and exercise. The students learn AM process knowledge and
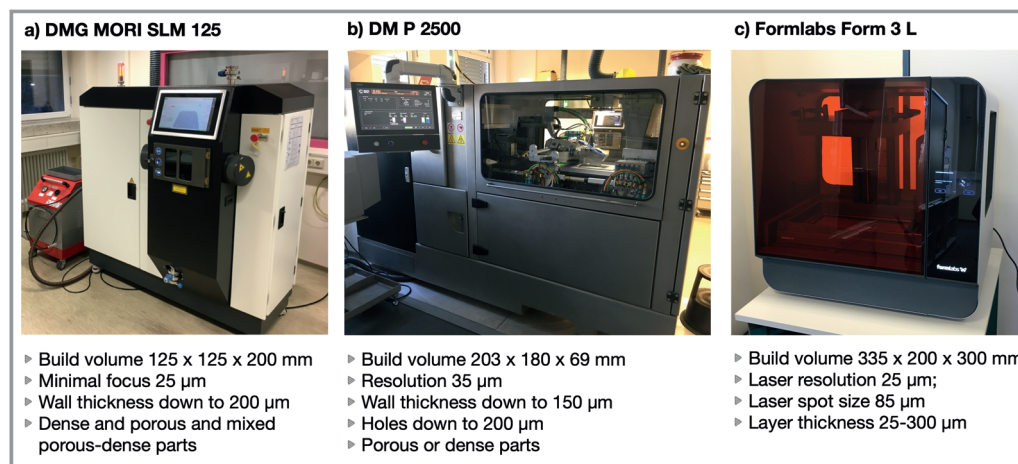

a) DMG MORI SLM 125	b) DM P 2500	c) Formlabs Form 3 L
▸ Build volume 125 x 125 x 200 mm	▸ Build volume 203 x 180 x 69 mm	▸ Build volume 335 x 200 x 300 mm
▸ Minimal focus 25 µm	▸ Resolution 35 µm	▸ Laser resolution 25 µm;
▸ Wall thickness down to 200 µm	▸ Wall thickness down to 150 µm	▸ Laser spot size 85 µm
▸ Dense and porous and mixed porous-dense parts	▸ Holes down to 200 µm	▸ Layer thickness 25-300 µm
	▸ Porous or dense parts	

Figure 1. 3D printers currently available at IMVT for practical training in AM. a) Realizer / DMG MORI SLM 125 (laser beam powder bed fusion, LB-PBF), b) Digital Metal 2500 P (binder jetting, BJ), c) Formlabs Form 3 L (stereo lithography, SL).
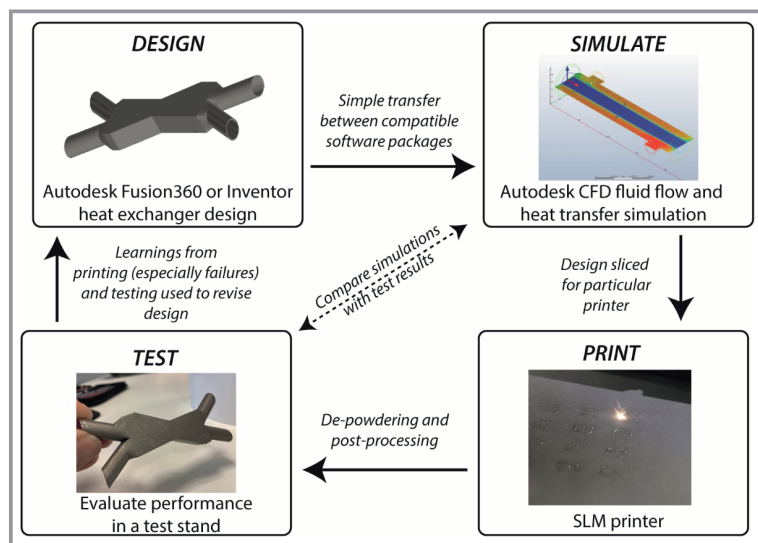
Figure 2. Teaching concept enabling the students to become makers.

design guidelines and apply the knowledge in the design of an AM part. Some courses include AM selection criteria and the choice of a part to be designed [14] while others provide students with a given part [15]. The advantages of the first approach are that the important skill of identifying good AM parts is included and that the motivation of students is higher when they work on their own parts. The advantages of a given part are an easier performance evaluation of students and the validation of the built parts in a single testing environment.

The required infrastructure and resources to offer courses on design for additive manufacturing are a sufficient amount of CAD licenses and workstations, at least one AM machine for in-house production of the designed parts and testing equipment to demonstrate the improvement of the part by designing for additive manufacturing. The inhouse production is important to give first-hand experience of the production process chain from build job preparation to the finishing of the part. Collaborating with external AM service providers is an option only when they are willing to build and share failed build jobs for a direct feedback on the feasibility of a part and the importance of design guidelines.

3 Structure of the Lecture and Practical Course

3.1 Lecture

The lecture material was delivered in four consecutive sections (cf. Tab. 1). In the first section, an introduction is given to the basic idea of AM, namely fabricating a distinctly shaped 3D object by adding shapeless material in layers in an automated process based on a digital 3D model of that object. It is made clear that AM is not one single technology but rather a multifaceted field, which has undergone rapid development with growth rates of 30 % per year. After this introduction the generic workflow of AM is explained [16–20].

To connect to process engineering, the concept of flexible and agile modular plants for production of specialty chemicals and active pharmaceutical ingredients is introduced (cf. Fig. 3), which represents a new direction in chemical process engineering targeting shorter time to market, customized production and improved economics, e.g., through plug-and-produce strategies relying on available standardized process equipment assemblies and plant reconfigurability [6]. Examples for modular plants at different scales are presented, also addressing the aspect of automation of custom-made synthesis routes, reaction optimization, design of molecules, and discovery of new functions based on artificial intelligence methods in order to demonstrate the actuality and relevance of this approach [21–24].
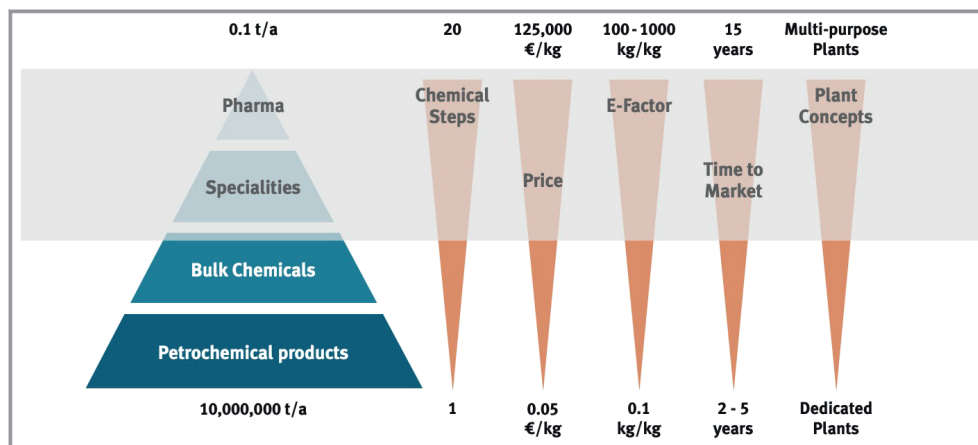
Table 1. Content of the lectures and allocation of time to the individual topics.

Section	Lecture hours
Introduction	2
– Generic principle and workflow of additive manufacturing	
– Manufacturing of components and devices for process engineering applications	
– The promise of additive manufacturing for process engineering	
Selected 3D printing methods	6
– Fused filament fabrication (FFF) / deposition modeling (FDM)	
– Vat polymerization / stereo lithography (SL) and photopolymer jetting (PJ)	
– Selective laser melting (SLM)	
– Binder jetting (BJ)	
Design for additive manufacturing	6
– Design principles	
– Data process chain	
– Data preparation software	
– Quality	
Applications	6
– Bioengineering	
– Flow chemistry	
– Energy	

Figure 3. Applicability of modular plant concepts [25].

Following, the potential of AM for supporting the development of novel key components for high-performing process equipment assemblies for modular plants is deduced from this reasoning, illustrated by examples from own research [26–28] and emphasizing that AM enables, on one hand, a new quality of fully digital simulation-assisted design and fabrication of advanced process equipment, but, on the other hand, also calls for design automation to exploit its full potential for speeding up the development cycle.

The second section provides an overview of the most important AM methods including the historical development of the field (cf. Fig. 4). Fused filament fabrication, stereo lithography and photopolymer jetting, laser beam powder bed fusion, and binder jetting are explicitly covered.

The working principles of all these methods are briefly introduced like shown exemplarily in Fig. 5, an overview of the materials that can be processed with them is given, and
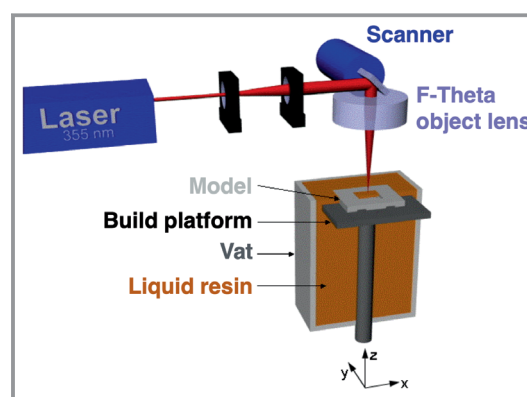

Figure 5. Stereo lithography as an example for the basic principle of 3D printers.

the basic characteristics of the printed parts, such as isotropy or anisotropy of the mechanical properties, strength, resistance against temperature and chemicals are discussed, in particular with a view to their use for process engineering applications. Commercially available machines from different manufacturers are shown together with examples of objects fabricated with them. For each AM method, at least one prominent exemplary application in process engineering from the scientific literature is presented and discussed to show the relevance of the method [29–38].

Moreover, the RepRap.org community [39] 3D printing project (cf. Fig. 6) is introduced through illustrative videos from the internet to make the students aware of the maker community.

In the third section, the minimum necessary skills and techniques to successfully participate in the design → simulate → print → test cycle were taught, including a basic introduction to Autodesk Fusion 360 or Inventor (for simple 3D design) and Autodesk CFD (for simple fluid flow and heat transfer CFD simulations). It is of

Figure 4. Overview on materials and functional principles of selected AM methods. Table from Klahn et al. [20]. SL, stereo lithography; PJ, photopolymer jetting; BJ, binder jetting; selective laser melting; EBM, electron beam melting; FDM, fused deposition modeling; SLS, selective laser sintering; MJM, material jetting.

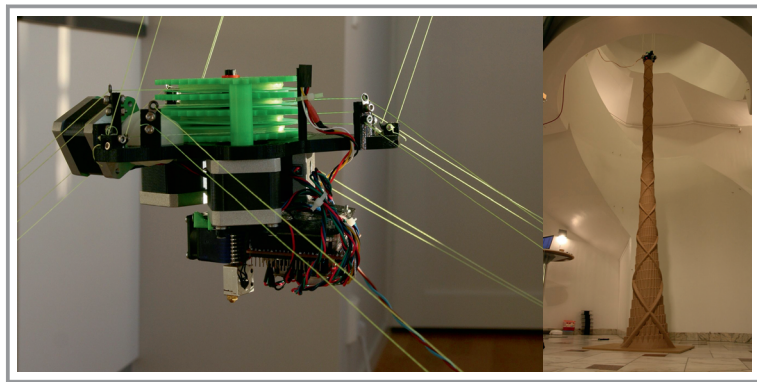© 2022 The Authors. Chemie Ingenieur Technik published by Wiley-VCH GmbH

Figure 6. RepRap.org – A 3D printing community project. Printing large objects with hangprinter [40].

course the case that many different CAD and CFD software packages are available, and for this course the offerings of Autodesk were chosen as the software is relatively straightforward (especially Fusion 360, an entry-level CAD package) and free education licenses are available for students and educators. Customized lectures and short videos were used to teach only the most essential elements, while signposting to more comprehensive tutorials and training materials was provided for the more interested students. Throughout this section of the course, the design philosophy of "Design for Additive Manufacturing" was embedded in the teaching, drawing on the concepts described by Diegel et al. [18].

One interesting educational aspect in this section of the course was to illustrate the design → simulate workflow with a simple concentric tube heat exchanger, showing all the steps necessary to complete the design, export to the CFD software, and set up the fluid flows and boundary con-

ditions to conduct simple steady-state and dynamic simulations. This was compared to the effort required to solve the steady-state heat transfer by hand, which is non-trivial.

During this part of the course, the practical started so that students could immediately make use of their new skills in practice. This close coupling between taught material in lectures and the ability of students to immediately implement and build on their learning with practical examples was beneficial for student learning, in particular as they started to design their own heat exchangers, they could ask questions or seek help with learning the software in parallel.

The fourth section of the lectures covered a range of exemplary applications of AM, including energy and biomedical fields. With the aim to facilitate the consolidation of this new information and expertise, we selected applications supposed to be familiar to master students (cf. Fig. 7). The examples presented in class covered a short introduction to real-world applications of the subjects (e.g., printing of anatomical models for surgical planning). Then the printing techniques were proposed by the students in a round table approach, before looking into how it was solved in the examples presented. The student's response was remarkable making evident the effectiveness of an integrative approach of lectures and practical work.

3.2 Practical

Based on problem-based teaching, the accompanying practical course was intended to strengthen the students' knowledge from the lecture. In six biweekly classes a functional
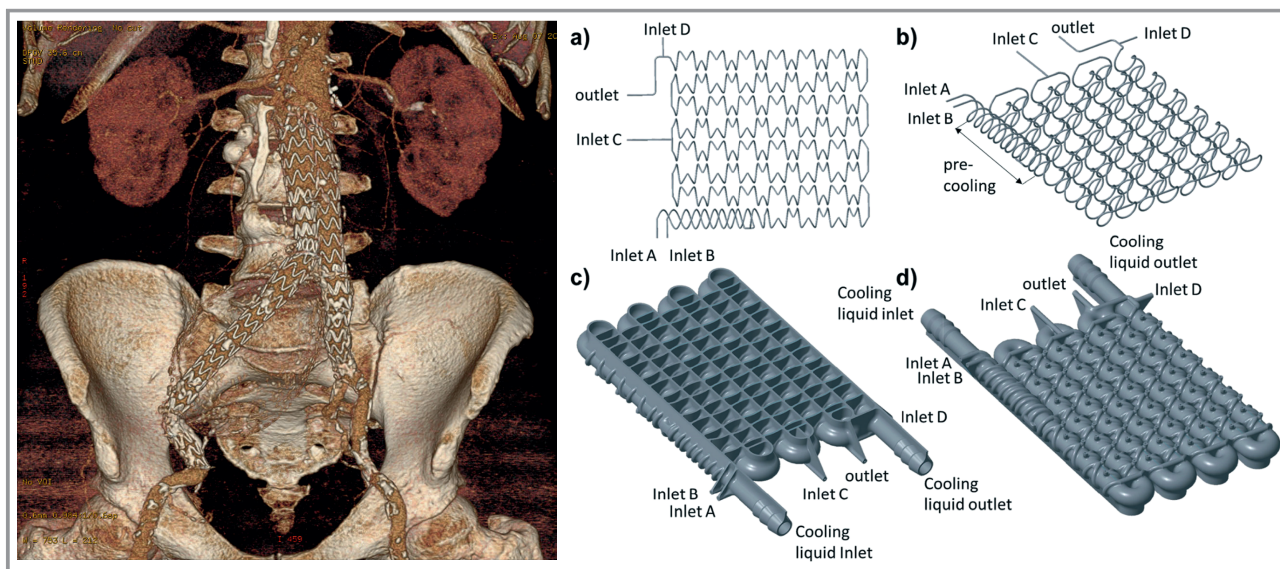

Figure 7. Exemplary applications of AM presented during the lectures. Left: 3D reconstruction of an aneurysm (from Ref. [41] with permission from Elsevier). Right: CAD drawings of a flow reactor for difluoromethylations (from Ref. [42] with permission from the Royal Society of Chemistry).

device should be designed and evaluated in silico and in real by each student. The task should be based on a chemical engineering problem. However, the task should be in such a manner that it allows a fast and direct feedback about the design without toxic substances and large evaluations and measurement setups. The design of a heat exchanger offered itself for this as a component of almost all process plants and the possibility to test it with water. For the evaluation a simple test stand consisting of two thermostats and a thermocouple transducer display was set up, shown in Fig. 8. For the connection of the heat exchangers hose connections with simple clamps for quick change between counter-current and cocurrent were chosen. This solution has the advantage that only a simple pipe socket has to be provided and no postprocessing, such as thread cutting, is necessary. Ideally, a suitable design will allow direct plug and play after printing. For the evaluation of the heat balance thermo-couples are in the connecting lines before the hose connectors. The design was done with the CAD software Autodesk Fusion 360 or Inventor. Between the practical meetings, employees at IMVT printed and postprocessed the drafts of the students. All of the designs were printed in 316 L with the DMG MORI SLM 125 unit shown in Fig. 1.
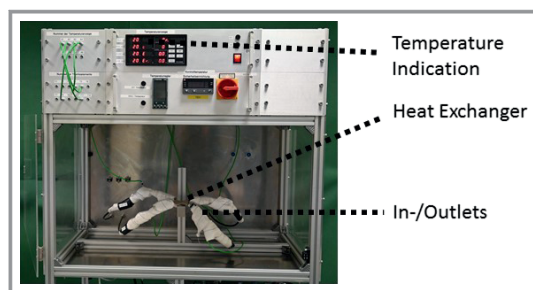

Figure 8. Test rig for the evaluation of the printed heat exchangers.

4 Results and Experiences from the First Two Years

The number of participants was not huge, but the participants were all the more enthusiastic with the willingness to invest a lot of time in the course to create a working heat exchanger (cf. Fig. 9). In the first practical sessions, we helped the students to get their thoughts and ideas from a sketch sheet of paper into a printable CAD-file. Since at KIT for chemical and bioengineers CAD is not a part of the curriculum, this was first a bit challenging for the students. Therefore, from winter term 2021 on we also offer a lecture for digital design for process engineers. Nevertheless, the students showed a steep learning curve, and some came up with advanced design especially for the internal structures of the heat exchangers like gyroids. Still, most of them were inspired by conventional designs like tube exchangers or plate heat exchangers. The main challenges were then to adapt the design – especially for the more conventional

Figure 9. Different printed heat exchangers from the course. They clearly show the motivation and creativity of the participants.

ones – in a way that they were printable. The main problem most students faced was how to connect the internal structure to the hose without an impossible overhang.

As teachers we further recognized that it is difficult to guide the students without restricting creativity or bringing already a design to their mind. For instance, giving a maximum build space of, e.g., $50 \times 50 \times 50 \, \text{mm}^3$ results in mostly heat exchangers utilizing the whole space. Here a volume or weight limit could help to give the students the freedom of a bigger design space without extreme long printing times, which otherwise make the production "just-in-time" nearly impossible. The same holds for minimum wall thicknesses, overhangs, and minimum hole diameters, as the students mostly tend to go to the limits to increase the performance of their heat exchangers. For the latter especially, a loop of printing, post processing, and evaluation helps. Consequently, we guided the students in the meetings and pointed out obvious problem areas in their designs. However, we intentionally printed also those parts that we knew would become a "misprint". Seeing the result on their own part, e.g., an overhang with spraying water due to a hole, helped students much more than just telling them or showing them examples. This was also seen in their final oral exam. We recognized that students could better explain the design guidelines and problems of additive manufacturing if they had "trouble" with their parts in the practical. However, the number of cycles was limited due to the time, and the time till they had their first design. This highlights the fact that one should design such a course and practical with as many iteration cycles as possible. In the first year, we underestimated this a bit and gave the participants too much time until they should have their first model printed. In the second year, we encouraged the participants to submit a first draft earlier in order to print it. This also helped us to schedule the prints better. With all these learnings, we could increase the number of working heat exchangers from around 30 % to around 70 % from the first to the second year.

5 Conclusions

Starting with a clean slate, we have developed a new course on AM for chemical and bioengineers at KIT as a synergistic mix of traditional lecture-based learning, practical learning with computer software packages, and perhaps most importantly, the ability to print real metal devices and test their performance. The concept is embodied in a design → simulate → print → test cycle that allows students to develop their own creative designs; in this case for a small compact heat exchanger, which allows for simplicity of design (so that students can complete the design cycle in the time allowed), but enough degrees of freedom that they can, and did, produce a wide range of highly original designs. Student feedback was positive and student learning outcomes (proxy measure being their course outcome) were uniformly high, no students failed the course in the first two years. We are convinced the course provides important engineering skills in an aspect of process engineering, which is undergoing rapid growth.

Abbreviations

AM   Additive Manufacturing
BJ   Binder jetting
EBM   Electron beam melting
FDM   Fused deposition modeling
FFF   Fused filament fabrication
LB-PBF   Laser-beam powder bed fusion
MJ   Material jetting
PJ   Photopolymer jetting
SL   Stereo lithography
SLM   Selective laser melting
SLS   Selective laser sintering

References

[1] E. Forrest, Y. Cao, *Eng. Manage. Res.* **2013**, *2 (2)*, 66–70. DOI: https://doi.org/10.5539/emr.v2n2p66

[2] D. W. Rosen, C. C. Seepersad, T. W. Simpson, C. B. Williams, *J. Mech. Des.* **2015**, *137 (11)*, 110301. DOI: https://doi.org/10.1115/1.4031470

[3] A. Vafadar, F. Guzzomi, A. Rassau, K. Hayward, *Appl. Sci.* **2021**, *11 (3)*, 1213. DOI: https://doi.org/10.3390/app11031213

[4] J. J. Beaman, D. L. Bourell, C. C. Seepersad, D. Kovar, *J. Manuf. Sci. Eng.* **2020**, *142 (11)*, 110812. DOI: https://doi.org/10.1115/1.4048193

[5] I. J. Petrick, T. W. Simpson, *Research-Technology Management* **2013**, *56 (6)*, 12–16. DOI: https://doi.org/10.5437/08956308X5606193

[6] *Modular Plants Flexible chemical production by modularization and standardization – status quo and future trends*, Temporärer ProcessNet-Arbeitskreis „Modulare Anlagen", Frankfurt **2016**.

[7] A. Stern, Y. Rosenthal, N. Dresler, D. Ashkenazi, *Addit. Manuf.* **2019**, *27*, 503–514. DOI: https://doi.org/10.1016/j.addma.2019.04.001

[8] www.vdi-wissensforum.de/lehrgaenge/fachingenieur-additive-fertigung-vdi/ (Accessed on January 30, 2022)

[9] www.dvs-home.de/bildung/additive-fertigung/fachkraft-3d-druck (Accessed on January 30, 2022)

[10] www.swissmem-academy.ch/de/kurse/additive-manufacturing-einfuehrung.html (Accessed on January 30, 2022)

[11] www.academy.fraunhofer.de/de/weiterbildung/fertigungs-prueftechnik/3d-druck-seminarreihe/additive-academy.html (Accessed on January 30, 2022)

[12] www.inspire.ethz.ch/de/kurse-weiterbildung/inspire-academy-kurse/programm/design-for-3d-printing/ (Accessed on January 30, 2022)

[13] B. Leutenecker-Twelsiek, J. Ferchow, C. Klahn, M. Meboldt, in *Industrializing Additive Manufacturing – Proceedings of Additive Manufacturing in Products and Applications – AMPA2017* (Eds: M. Meboldt, C. Klahn), Springer International Publishing, Cham **2018**.

[14] J. F. Ferchow, C. Klahn, M. Meboldt, in *DS 93: Proceedings of the 20th International Conference on Engineering and Product Design Education (E&PDE 2018)*, London, September **2018**.

[15] A. Kirchheim, H.-J. Dennig, L. Zumofen, in *Industrializing Additive Manufacturing – Proceedings of Additive Manufacturing in Products and Applications – AMPA2017* (Eds: M. Meboldt, C. Klahn), Springer International Publishing, Cham **2018**.

[16] I. Gibson, D. Rosen, B. Stucker, M. Khorasani, *Additive Manufacturing Technologies*, Springer International Publishing, Cham **2021**.

[17] *Additive Fertigung, Stellungnahme* (Eds: M. Kohlhuber, M. Kage, M. Karg), acatech – Deutsche Akademie der Technikwissenschaften/Nationale Akademie der Wissenschaften Leopoldina/Union der Deutschen Akademien der Wissenschaften, München/Halle (Saale)/Mainz **2016**.

[18] O. Diegel, A. Nordin, D. Motte, *A Practical Guide to Design for Additive Manufacturing*, Springer Singapore, Singapore **2019**.

[19] E. Pei, M. Monzón, A. Bernard, *Additive Manufacturing – Developments in Training and Education*, Springer International Publishing, Cham **2019**.

[20] *Additive Fertigung* (Eds: C. Klahn, M. Meboldt), 2nd ed., Vogel Communications Group, Würzburg **2020**.

[21] M. Trobe, M. D. Burke, *Angew. Chem., Int. Ed.* **2018**, *57 (16)*, 4192–4214. DOI: https://doi.org/10.1002/anie.201710482

[22] K. Williams, E. Bilsland, A. Sparkes, W. Aubrey, M. Young, L. N. Soldatova, K. de Grave, J. Ramon, M. de Clare, W. Sirawaraporn, S. G. Oliver, R. D. King, *J. R. Soc., Interface* **2015**, *12 (104)*, 20141289. DOI: https://doi.org/10.1098/rsif.2014.1289

[23] A. G. Godfrey, T. Masquelin, H. Hemmerle, *Drug Discovery Today* **2013**, *18 (17–18)*, 795–802. DOI: https://doi.org/10.1016/j.drudis.2013.03.001

[24] I. Clift, *Gen. Eng. Biotechnol. News* **2019**, *39 (8)*, 30–33. DOI: https://doi.org/10.1089/gen.39.08.09

[25] D. Schmalz, F. Stenger, A. Brodhagen, A. Schweiger, T. Bieringer, C. Dreiser, *Towards modularization and standardization of chemical production units: status quo, development needs, and current activities*, Dechema Praxisforum Future Production Concepts in Chemical Industry, Frankfurt **2016**.

[26] E. Hansjosten, A. Wenka, A. Hensel, W. Benzinger, M. Klumpp, R. Dittmeyer, *Chem. Eng. Process.* **2018**, *130*, 119–126. DOI: https://doi.org/10.1016/j.cep.2018.05.022

[27] F. Grinschek, D. Xie, M. Klumpp, M. Kraut, E. Hansjosten, R. Dittmeyer, *Ind. Eng. Chem. Res.* **2020**, *59 (9)*, 3736–3743. DOI: https://doi.org/10.1021/acs.iecr.9b04548

[28] D. Xie, R. Dittmeyer, *Addit. Manuf.* **2021**, *47*, 102261. DOI: https://doi.org/10.1016/j.addma.2021.102261

[29] P. J. Kitson, G. Marie, J.-P. Francoia, S. S. Zalesskiy, R. C. Sigerson, J. S. Mathieson, L. Cronin, *Science (New York, N.Y.)* **2018**, *359 (6373)*, 314–319. DOI: https://doi.org/10.1126/science.aao3466

[30] F. Kotz, P. Risch, D. Helmer, B. E. Rapp, *Adv. Mater.* **2019**, *31 (26)*, e1805982. DOI: https://doi.org/10.1002/adma.201805982

[31] C. Prechtl, M. Kraut, M. Franzreb, G. Brenner-Weiß, R. Dittmeyer, *Chem. Eng. Technol.* **2017**, *40 (4)*, 670–677. DOI: https://doi.org/10.1002/ceat.201600395

[32] C. Y. Yap, C. K. Chua, Z. L. Dong, Z. H. Liu, D. Q. Zhang, L. E. Loh, S. L. Sing, *Appl. Phys. Rev.* **2015**, *2 (4)*, 41101. DOI: https://doi.org/10.1063/1.4935926

[33] S. Vock, B. Klöden, A. Kirchner, T. Weißgärber, B. Kieback, *Prog. Addit. Manuf.* **2019**, *4 (4)*, 383–397. DOI: https://doi.org/10.1007/s40964-019-00078-6

[34] C. Parra-Cabrera, C. Achille, S. Kuhn, R. Ameloot, *Chem. Soc. Rev.* **2018**, *47 (1)*, 209–230. DOI: https://doi.org/10.1039/c7cs00631d

[35] C. H. Hornung, *Science (New York, N.Y.)* **2018**, *359 (6373)*, 273–274. DOI: https://doi.org/10.1126/science.aar4543

[36] S. Girnth, J. Koopmann, G. Klawitter, N. Waldt, T. Niendorf, *Prog. Addit. Manuf.* **2019**, *4 (4)*, 399–409. DOI: https://doi.org/10.1007/s40964-019-00082-w

[37] W. Du, X. Ren, Z. Pei, C. Ma, *J. Manuf. Sci. Eng.* **2020**, *142 (4)*. DOI: https://doi.org/10.1115/1.4046248

[38] S. Mirzababaei, S. Pasebani, *J. Manuf. Mater. Process.* **2019**, *3 (3)*, 82. DOI: https://doi.org/10.3390/jmmp3030082

[39] https://reprap.org/wiki/RepRap.

[40] www.youtube.com/watch?v=ULJqLSTriRY (Accessed on January 30, 2022)

[41] A. Marro, T. Bandukwala, W. Mak, *Curr. Probl. Diagn. Radiol.* **2016**, *45 (1)*, 2–9. DOI: https://doi.org/10.1067/j.cpradiol.2015.07.009

[42] B. Gutmann, M. Köckinger, G. Glotz, T. Ciaglia, E. Slama, M. Zadravec, S. Pfanner, M. C. Maier, H. Gruber-Wölfler, C. Oliver Kappe, *React. Chem. Eng.* **2017**, *2 (6)*, 919–927. DOI: https://doi.org/10.1039/C7RE00176B