Structured Approach for Changing Designer's Mindset Towards Additive Manufacturing: From Theory to Practice

Gustavo Menezes de Souza Melo[1(✉)], Gerret Lukas[2], Johannes Willkomm[1], Stephan Ziegler[1], Günther Schuh[2], and Johannes Henrich Schleifenbaum[1]

[1] Chair for Digital Additive Production (DAP), RWTH Aachen University, 52074 Aachen, Germany
gustavo.melo@dap.rwth-aachen.de
[2] Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, 52074 Aachen, Germany

Abstract. Additive Manufacturing (AM) has a great potential of disrupting product design and supply-chain in many industries by means of its unique capabilities. Regarding the product design, the potential benefits comprise functional integration, reduced assembly efforts, reduced weight and increased performance. Although AM has been around for decades, designers still think in the restrictions imposed by conventional manufacturing. The awareness of the potentials of AM has not yet been pushed in the minds of designers and the adoption of AM in design process often fails due to a status quo in design or limited knowledge of the employees. Against this background, this paper proposes a framework to change Designer's mindset towards AM. By means of in-depth interviews with designers and design engineers from different industries, the common challenges and implemented solutions were investigated. From these expert interviews, the following key challenges were identified: AM-adjusted design methodology, standards implementation and software support. Based on those, a wide literature review of possible solutions was carried out and its result was combined with the already implemented solutions in industry. The proposed framework not only takes advantage of currently available human capital in the organization but also paves a sustainable way to train new personnel and create momentum towards AM adoption. By means of a structured learning path and a knowledge management platform integrated into design software, the proposed framework effectively extracts tangible and part-specific design rules and assures optimal knowledge transfer among employees. This framework was subsequently validated in a workshop with industry experts.

Keywords: Additive Manufacturing · Design methods · DfAM · Product development · Change management

M. Meboldt and C. Klahn (Eds.): AMPA 2020,
Industrializing Additive Manufacturing, pp. 17–25, 2021.
https://doi.org/10.1007/978-3-030-54334-1_2

1 Introduction

AM has been emerging strongly in recent years. Growth in machine sales and increased numbers of equipment manufacturers show how the AM market has been expanding [1]. AM enables the fabrication of products with high complex design with various functionalities [2–4]. However, design engineers often think in the restrictions imposed by conventional manufacturing or link AM to unrealistic expectations [2]. The awareness of the potentials and restrictions of AM has not been effectively pushed in the minds of design engineers. Moreover, the adoption of AM in design process often fails due to a status quo in design or limited knowledge of the employees. A sustainable adoption of AM is only possible by means of complete mindset shift of designers and design engineers from conventional manufacturing towards AM [3]. In other words, today's professionals need to change the way they approach design problems. Against this background, some companies have already started their journey to train their employees in AM.

Academic literature has dealt with education in the field of AM for almost a decade. Since AM has been of growing interest, Geraedts et al. [4] investigated the role of AM in the light of design engineering in three domains: business, research, and education. At the same time Williams and Seepersad [5] developed a concept combining project-based and problem-based learning for a university course. In both papers, the dominant topic was education for future designers in AM. Then, Ford and Dean [6] discussed the general necessity of teaching conventional manufacturing in comparison to AM. They conclude that designer should not ignore conventional design and AM should be added to the curriculum. A sole focus on AM could result in diminishing conventional technologies. Loy [7] puts this conclusion into a different perspective, by stating that design educators face a number of different challenges in terms of AM in design education. Minetola et al. [8] use a survey to investigate the impacts of early exposure with AM in engineering education and find that a "think-additive" approach early on leads to a full facilitation of the benefits of AM. Simpson et al. [9] and Prabhu et al. [10] conclude in a similar way. Yet, only Watschke et al. [11] propose a methodical approach for design education, however they focus on the ideation process.

In the light of previous and current research, the prevailing need of companies for designer with an AM mindset has not yet been addressed. As researcher focused on the secondary and tertiary education to train future talent, the education for professionals, also referred as continuing education, has been neglected. Of course, educating professionals in AM is core to a number of certificate courses and workshops, but literature does not provide a systematic approach that addresses the needs of companies. Therefore, this paper aims to develop a systematic framework to educate design engineer professionals and provide insight into the development of an AM mindset in industrial companies.

Against this background, this paper presents a survey among industry participants for a deeper understanding of challenges, goals and current implemented solutions in companies. Subsequently, a broad literature study is carried out in order to collect further best practices among the academia and industry beyond our focus group. Finally, based on the two steps before mentioned, a systematic framework is developed and validated through a workshop with the interview participants.

2 Method

The presented research utilizes qualitative research. AM mindset cannot be described by a defined set of variables, it rather emerges from a dynamic model based on qualitative data: In order to generate such data, we used two types of methods. We base on the concept for grounded theory [12] as we obtain data by interviewing a group of representatives of companies that facilitate AM in their organization. In addition to the interviews, we conducted a systematic review of existing literature based on codes from the interviews. Table 1 gives an overview of the addressed industries. The participants of each company are in charge of the AM activities and are ranked in middle management.

Table 1. Overview of interview participants.

Industry	Number of companies	Number of participants
Machine manufacturing	3	3
Automotive	3	3
Materials & process	4	4

The interviews were semi-structured, conducted by one of the authors and recorded for documentation purpose. Before the interview, the participants received a guideline containing seven open questions to prepare the interview. During the interview, the interviewer could alter the question, if needed, to enlarge on topics of interest for the study. In order to keep track of such changes to the guidelines, interview reviews were conducted and if necessary the guidelines were adjusted. However, every participant was only interviewed once. After all interviews were conducted, we coded the transcripts and categorized findings. Our three main categories were "common challenges", "implemented solutions" and "shared goals". As our participant group was small compared to other qualitative studies, we ensured iteration between initial coding and categorizing for an objective analysis of the interview data.

Subsequently to the interviews, a systematic literature review based on the procedure by Kitchenham [13] was applied. This systematic is divided into three phases: planning, conducting and reporting. Within the planning phase the objectives of the literature review was defined. From the interviews ("common challenges" and "shared goals"), three key areas were identified as vital for mindset shift towards AM:

- AM-adjusted design methodology, which raises awareness and increase know-how
- Implementation of standards, which uses a structured and accessible approach
- Provision of better software, which supports expert knowledge exchange

During the conductive phase, the literature was collected and analysed. For this purpose, the literature was divided in two categories according to their scientific value: primary source (e.g. paper, standards and technical books) and second source (e.g. magazine, internal knowledge and online guidelines). By means of the systematic proposed by Kitchenham, numerous literature studies were screened, with a focus on the last decade. The identified literature was subsequently presented to in-house AM design experts who selected the most relevant and comprehensive ones. In the reporting phase, the literature is summarized and reported for further investigation.

3 Result

The goal of the interviews in our study group was obtaining a description of the status quo of continuing education for AM at the respective companies. During the coding of the interviews, we identified emerging themes via our in-vivo codes, as exemplified in Table 2. We avoided any early categorization for an objective analysis of the data [14]. At the end of our interview transcription and coding, we found that three categories were fitting our themes and codes best: "common challenges", "implemented solutions", and "shared goals".

Table 2. Examples from in-vivo codes, themes, and categories.

In-vivo code	Theme	Category
"However, we are still in the learning phase. You get the standard design rules, but often it's still try and fail and then redesign."	Design methodology	Common challenges
"The very first fruitful way was that we sent designers to user training."	Design training	Implemented solutions
"Certification of components: This is a K.O. criterion for us. If there is not something clearer there, I do not know whether it [AM] goes on here."	Certification	Shared goals

Among the challenges, we identified in our study, AM know-how and methods for continuing education in particular were the most relevant topics for the majority of the partners. While software and norms were the second and third largest concerns. "Implemented solutions" summarize indication for approaches to solve the challenges along the implementation of an AM mindset. Unsuccessful solutions have led to remaining issues in the category of "Common challenges". Across our interviewee group we found a number of different approaches. Very common was to establish an in-house expert team responsible to develop and hold workshops in different aspects of AM. Those teams also managed internal databases for design guidelines and best-practice projects. In summary, three categories of implemented solutions were identified: Collecting information through learning by doing, creation of own guidelines, and discussion with experts in user groups. However, there is agreement among the participant that the challenges still remain and the shared goals have not yet been reached. A new type of design methodology has to be established. This methodology must be adapted to AM. Furthermore, the new methodology needs support by international standards and procedure for certification. Lastly, due to the complexity, software tool must improve and be able to support decisions faced by designers.

Throughout the literature review study, it is elaborated that an AM-adjusted design methodology requires not only AM design workflow, but also the key design guidelines and how effectively learn DfAM. Among the most important workflows are the one from ASTM 52910 (Additive manufacturing—Design—Requirements, guidelines and recommendations) [15] and workflow of approaches typically enabled by AM (e.g.: topology optimization [16], cellular materials – lattice structures [17], monolithic design – part consolidation [2], and function integration [18]). In the topic of design guidelines, besides the major reference ASTM 52910, online available guidelines were suggested along recent and updated AM design books (e.g.: A Practical Guide to Design for Additive Manufacturing) [19]. Lastly, the most suitable learning approaches for DfAM were presented, from lecture, through problem until project-based learning [5, 20].

Regarding the implementation of standards, key norms, handbooks and guidelines were covered. Among those are the already mentioned ASTM 52910 and the VDI 3405 – part 3 [21]. The most valuable contribution is the method which describes how to implement those guidelines. In general, the AM industry currently lacks fundamental principles for establishing derivative rules based on guidelines and best practices. To be useful to designers, design guidance needs to consist of rules with numeric values capturing the limitations of AM technologies, processes, and machines. The Guide-to-Principle-to-Rule Approach offers a structured implementation framework from the abstractness of design guidelines, through design principles, until the concreteness of design rules [22].

Concerning the provision of better software, three phases throughout the product design process were delimited: before, during and after design. Before design, some solutions based on Artificial Intelligence (AI)/Augmented Intelligence were presented as promising, e.g.: AI sketch-based design tool [23]. During design, the most established solution was generative design, along with new coming approaches as real-time generative-design (e.g. Autodesk and Desktop Metal Live Parts). Lastly after design, printability checker and build simulation analysis tools are the most common used ones (e.g. ANSYS).

4 Development and Validation of Framework

The broad literature review demonstrated that continuing education is key actor to raise awareness, increase know-how and knowledge exchange. Moreover, a structured approach was presented to extract, from high level guidelines presented in standards, consistent and tangible rules for their wider adoption. Lastly, software works as a right support to enhance human capabilities, acting as soon as possible in the design process. Based on those findings, a holistic solution was proposed.

The solution takes into account two main important aspects: the product and the individual. The first, represented here by the product design process, ranges from conceptual to final design. The second, represented here by the design knowledge, ranges from novice to expert. On one hand, the final design requires an expert level of knowledge, on the other, novices perform better and more innovative than experts during the conceptual phase of product design due to lack of fixation [24, 25]. The solution is presented through the framework in Fig. 1.

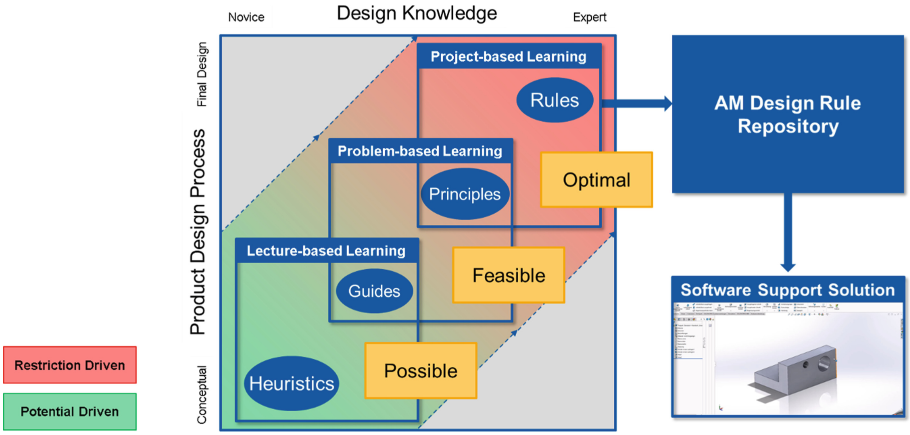

Fig. 1. Framework with structured learning path, objectives and final output used in assistant for design software.

This path from conceptual to final design optimally linking novice and expert knowledge is assured by means of different learning methods, from lecture, via problem and lastly project-based. Firstly, lecture-based learning explores what is possible through AM, presenting some approaches and features to be used in this sense. Problem-based learning aims the correlation design-material-process and their trade-off to meet requirements (from a client, for example). Lastly, project-based learning addresses how to quantify restrictions, being therefore able to optimize regarding quality, cost and time.

Each learning phase covers, in different time frames – respectively days, weeks and months – specific topics in order to guarantee a transition from potential of additive manufacturing until its restrictions. The covered topics are design heuristics, guides, principles and rules. Design Heuristics are cognitive shortcuts that help designers explore variations in designs. Design Guides offer feature-based best practices when using AM in product design to take advantage of AM capabilities. Design Principles are basic, logical correlations capturing process parameter and control parameters. And Design Rules are explicit value-based constraints that provide needed insight into manufacturability. Those rules are subsequently stored in a knowledge repository which works as database for a software support application.

In conclusion, this integrated solution uses continuing education to raise awareness and improve knowledge exchange among professionals and uses a structured and optimal path to get concrete design rules from the abstractness of norm and standards. This proposed framework works therefore as a bridge between theory and practice in how to design for AM. Lastly, a software support application makes the knowledge developed during this learning process available for new design engineers and coming products.

By means of a workshop, the above mentioned solution was presented to representatives from interviewed companies in order to collect their industrial and business perspectives. At the end of the workshop, a round table discussion took place and the perspective of all participants was individually expressed and clarified. The proposed approach was positively evaluated by all participants of the workshop. Numerous valuable points came up from the discussion which are summarized below:

- Design for AM should cover not only the relations between material, properties and 3D printing process, but also post-processing;
- The proposed solution suits the niche of businesses with low product diversity and mid-series production due to the highly needed internal efforts and costs;
- In order to be scalable, as shareable approach should be merged into the solution for cost and risk sharing;
- OEMs play an important role in order to make this scalable solution possible. IP of design is the main point of attention;
- The main objective is to identify the right moment, financially speaking, to quit the learning track and use the shared knowledge base for desired design rules.

5 Conclusion and Outlook

The paper revealed that the interviewees have similar experiences regarding the continuing education of designers and other employees in AM. The design methodology, norms & standards and design software have been identified as key areas to improve AM adoption. The proposed solution consists of a structured framework to optimally take advantage of company's human capital and to extract tangible rules for 3D printing an optimal part, fostering alongside knowledge transfer and creating awareness. Lastly, a software application makes expert know-how more easily available with fewer resources. This integrated solution successfully tackle the three key areas identified as vital for mindset shift towards AM: AM-adjusted design methodology, implementation of standards and provision of better software.

However, our theory is grounded on a qualitative approach, thus cannot provide any statistical evidence. Nonetheless, the researched phenomena of continuing education for AM is no topic for quantitative research only. Therefore, we conclude that our model contributes to the understanding of professional continuing education for AM design, but can be extended by evaluating a larger group of employees on different hierarchical levels and professional tenure.

As outlook, the future work comprises the development of an open innovation platform for sharing of design rules. A first solution proposed is based on the automatically extraction of design rules via on-premise software, subsequently encryption and lastly upload to the cloud only after prior authorization of the respective IP owner. The main issue to be investigated is how refractory will be the industry to share their development in exchange of others.

References

1. Campbell, I., Diegel, O., Huff, R., Kowen, J., Wohlers, T.: Wohlers Report 2019: 3D Printing and Additive Manufacturing State of the Industry. Wohlers Associates, Fort Collins (2019)
2. Schmelzle, J., Kline, E.V., Dickman, C.J., Reutzel, E.W., Jones, G., Simpson, T.W.: (Re) designing for part consolidation: understanding the challenges of metal additive manufacturing. J. Mech. Des. **137**(11), 111404 (2015)
3. Ahuja, B., Karg, M., Schmidt, M.: Additive manufacturing in production: challenges and opportunities. In: Laser 3D Manufacturing II, California, vol. 9353. International Society for Optics and Photonics (2015)
4. Geraedts, J., Doubrovski, E., Verlinden, J., Stellingwerff, M.: Three views on additive manufacturing: business, research and education. In: Horváth, I., Albers, A., Behrendt, M., Rusák, Z. (eds.) Ninth International Symposium on Tools and Methods of Competitive Engineering, Karlsruhe, pp. 1–15 (2012).
5. Williams, C.B., Seepersad, C.C.: Design for additive manufacturing curriculum: a problem- and project-based approach. In: International Solid Freeform Fabrication Symposium, Virginia, pp. 81–92 (2012)
6. Ford, P., Dean, L.: Additive manufacturing in product design education: out with the old and in with the new? In: DS 76: Proceedings of E&PDE 2013, the 15th International Conference on Engineering and Product Design Education, Dublin, pp. 611–616 (2013).
7. Loy, J.: The future for design education: preparing the design workforce for additive manufacturing. Int. J. Rapid Manuf. **5**, 199–212 (2015)
8. Pei, E., Minetola, P., Iuliano, L., Bassoli, E., Gatto, A.: Impact of additive manufacturing on engineering education–evidence from Italy. Rapid Prototyp. J. **21**(5), 535–555 (2015)
9. Simpson, T.W., Williams, C.B., Hripko, M.: Preparing industry for additive manufacturing and its applications: summary & recommendations from a national science foundation workshop. Addit. Manuf. **13**, 166–178 (2017)
10. Prabhu, R., Miller, S.R., Simpson, T.W., Meisel, N.: The earlier the better? Investigating the importance of timing on effectiveness of design for additive manufacturing education. In: ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Quebec City, Canada (2018)
11. Watschke, H., Bavendiek, A.K., Giannakos, A., Vietor, T.: A methodical approach to support ideation for additive manufacturing in design education. In: DS 87-5 Proceedings of the 21st International Conference on Engineering Design (ICED 17): Vol 5: Design for X, Design to X, Vancouver, Canada, pp. 41–50 (2017).
12. Tweed, A., Charmaz, K.: Grounded theory methods for mental health practitioners. In: Harper, D., Thompson, A.R. (eds.) Qualitative research methods in mental health and psychotherapy, pp. 131–146. Wiley-Blackwell, Oxford (2012)
13. Kitchenham, B.: Procedures for performing systematic reviews, Keele, UK (2004)
14. Gummesson, E.: All research is interpretive! J. Bus. Ind. Mark. **18**, 482–492 (2003)
15. ISO/ASTM52910-18, Additive manufacturing—Design—Requirements, guidelines and recommendations. ASTM International, West Conshohocken, PA (2018)
16. Gebisa, A.W., Lemu, H.G.: A case study on topology optimized design for additive manufacturing. Mater. Sci. Eng. Conf. Ser. **276**(1), 012026 (2017)
17. Merkt, S., Klocke, F.: Qualifizierung von generativ gefertigten Gitterstrukturen für maßgeschneiderte Bauteilfunktionen, Aachen, Germany (2015)
18. Klaiber, D., Fröhlich, T., Vietor, T.: Strategies for function integration in engineering design: from differential design to function adoption. Procedia CIRP **84**, 599–604 (2019)

19. Diegel, O., Nordin, A., Motte, D.: A Practical Guide to Design for Additive Manufacturing. Springer, Singapore (2020)
20. Yang, L.: Introducing the state-of-the-art additive manufacturing research in education. In: Pei, E., Monzón, M., Bernard, A. (eds.) Additive Manufacturing: Developments in Training and Education, pp. 53–65. Springer, Cham (2019)
21. VDI 3405 Blatt 3:2015-12: Additive Fertigungsverfahren - Konstruktionsempfehlungen für die Bauteilfertigung mit Laser-Sintern und Laser-Strahlschmelzen (2015)
22. Mani, M., Witherell, P., Jee, H.: Design rules for additive manufacturing: a categorization. In: ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, Digital Collection, Ohio (2017)
23. Wang, F., Kang, L., Li, Y.: Sketch-based 3D shape retrieval using Convolutional Neural Networks. In: 2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Boston, MA, pp. 1875–1883 (2015)
24. Kim, J., Ryu, H.: A design thinking rationality framework: framing and solving design problems in early concept generation. Hum. Comput. Interact. **29**, 516–553 (2014)
25. Crilly, N.: Fixation and creativity in concept development: the attitudes and practices of expert designers. Des. Stud. **38**, 54–91 (2015)