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Advancing design for Additive Manufacturing Education: A focus on computational skills and competencies

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Abstract

Recent advances in digital fabrication are expanding the limits of fabricable real-world designs. Additive Manufacturing (AM) technologies allow exploring unconventional design solutions across all scales and fields in fundamental science and engineering practice. Over the past years, this possibility has established AM and Design for AM (DfAM) as integral parts of engineering design curricula. Educators and researchers in engineering design are thus highly interested in investigating how designers should be best educated to follow, utilize, and actively participate in this advancement in digital fabrication. However, despite this growing interest, studies describing teaching experiences focused on DfAM are still limited. Besides, almost no studies report on how DfAM education affects students' further academic studies or professional careers after exposure to the topic.

To address this gap and contribute to *educating the next generation of designers*, the paper conducts an online follow-up survey with alumni of two editions of the Computational Design for AM Summer School in an attempt to answer how the acquired knowledge, skills, and competencies impacted their studies, research, and professional careers in a long-term after their participation in the course. The discussion is augmented with the results of two supplementary surveys on the teaching experiences and students' feedback performed right after each summer school edition. Results show that participants are conscious of the potential long-term impact of the lived educational experience. Besides, the school's multidisciplinary environment and the implemented problem-based approach have been fundamental to creating an engaging and valuable learning experience.

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Introduction

Additive manufacturing (AM) technologies continuously evolve in processable materials, resolution, printing volumes, and quality (Leung et al., 2019; Rosen, 2014; Thompson et al., 2016). This evolution extends design boundaries and pushes the development of cutting-edge and high-added value ideas in various fields, from biomedical to architecture, from aerospace to product design, and computer graphics. Designers can now explore and develop tailored and advanced solutions by exploiting the potentialities of these technologies at the design level. Functional integration, multi-material printing, local and multi-scale tuning of properties, and highly complex organic shapes are only a few of the design opportunities available nowadays (Leung et al., 2019). However, it is worth noting that these design opportunities also extend current design paradigms (Gao et al., 2015; Rosen, 2014, 2016). The possibility, for example, of designing metamaterial (or architected materials) is opening new design scenarios beyond the established concept of material selection (Greer & Deshpande, 2019; Montemayor et al., 2015). The proper exploitation of such a wide range of opportunities calls for a new mindset that is strongly multidisciplinary and capable of mastering interlinked requirements. To create this mindset, computational and algorithm-based design strategies can contribute fundamentally (Leung et al., 2019; Liu et al., 2018; Rosen, 2016). Indeed, considering the increase in design complexity, they are essential to support designers in exploring the design space, modelling complex and multidisciplinary phenomena, and enabling the advanced control of the fabrication process.

The innovativeness of a 3D-printed solution relies on the ability of designers to successfully establish a trade-off among material properties, digital modelling, and the control of the manufacturing process while exploiting a wide range of design opportunities. In response to these design opportunities, a comprehensive survey of DfAM in higher education was conducted recently (Borgianni et al., 2022) to emphasize and promote the need for adopting DfAM into standard engineering design curricula. The survey also shows that most approaches to teaching DfAM use inductive problem- and project-based learning pedagogies, originally suggested by (Williams & Seepersad, 2012). There (Williams & Seepersad, 2012) it is argued that relying on smaller practical problem-solving tasks focused on knowledge acquisition or on one larger open-ended project-based task involving teamwork, knowledge application, and synthesis encourages students to comprehensively explore the possibilities and limitations of AM technologies. To support such courses, the teaching staff serves as course instructors, tutors and facilitators. For example, the work (Thomas-Seale et al., 2022) reports on the diffusion of DfAM principles in teaching through a project-based learning approach: it positively impacts students' consciousness about their level of knowledge, self-efficacy, and capabilities in addressing a DfAM challenge, i.e., an open-ended design project. Similar to standard engineering design curricula (Dym et al., 2005), the students benefit from the DfAM challenge problem, which reflects the design practice and also, at the same time, frames the overall learning objectives (Williams & Seepersad, 2012). DfAM courses can use a hybrid model between a standard classroom approach and problem-based learning (Diegel et al., 2019). The work reports that the inductive approach to teaching based on project-based learning contributes to knowledge acquisition and overall course satisfaction, in contrast to standard classroom practices relying primarily on memorizing the course material. The works from (Diegel et al., 2019) and (Williams et al., 2015) also report a team-based course organization to the DfAM design challenge. Such informal learning environments are set to mimic real-life professional situations (Sawyer, 2005) and prove beneficial for motivating students and enhancing their skills in leadership, collaboration, communication, and innovation (Williams et al., 2015). To implement project-based approaches, it is also fundamental to provide students with suitable methodologies and tools to push them to think outside conventional manufacturing paradigms, as demonstrated in academic and industrial teaching environments (Blösch-Paidosh & Shea, 2021, 2022). For example, the study (Prabhu et al., 2020) investigated how the educational content of a DfAM course affects the students' use of DfAM in the engineering design process. The study concludes that to push students to exploit AM in the design, future teaching practices need to include concepts emphasizing the capabilities and opportunities of AM rather than focusing on AM limitations. The teaching modality can also play a relevant role. A recent study (Schauer et al., 2022) has highlighted that the virtual teaching modality could give students more "freedom" to express their creativity when asked to implement DfAM principles because in-person suggestions could limit their inventiveness. The study also showed that the adoption and use of DfAM principles are almost equal when comparing virtual and in-person environments and concluded that more research is required to pinpoint the exact sources behind the creativity block occurring in in-person environments.

To explore how to train the next generation of designers for AM, the authors have designed and offered an international summer school on Computational Design for AM. This paper shares the educational drivers that pushed the authors to organize the summer school and summarizes the feedback collected from the participants. The summer school is intended for selected international master's and PhD students and aims to explore and apply the potential of computational-based strategies in Design for Additive Manufacturing (DfAM). As shown in the relevant literature (Leung et al., 2019; Liu et al., 2018; Rosen, 2016), computational and algorithm-based design strategies are essential to creating a mindset capable of designing for AM; they help designers exploit AM's potential at the design and fabrication levels. Successful implementation of these strategies enables the exploration of the design space, mastering interlinked requirements, stimulates the modelling of complex and multidisciplinary phenomena, and supports the advanced control of the fabrication process. The IDEA League alliance (https://idealeague.org) has promoted and supported the two editions of the school (i.e., 2020 and 2021). The school has so far taken place online due to the COVID-19 pandemic. The authors also served as course instructors, tutors, and facilitators for both instances of the summer school.

The paper aims to reflect on these two school editions and investigate how DfAM education has affected participants' academic studies and professional careers after being exposed to the topic. Insights are derived based on an online follow-up questionnaire shared with the summer school alumni with a time lag of at least 1 year after the summer school ended. The aim of preparing the questionnaire is twofold: (1) to identify issues with previous offerings and propose new actions for improving the educational experience and (2) to understand whether the acquired knowledge, skills and competencies have influenced participants' careers in the long term. The motivation stems from the fact that almost no studies report on how DfAM education affects students' further academic studies or professional careers after exposure to the topic. Based on the questionnaires' results, this work draws conclusions outlining how to advance DfAM education, especially as it relates to short-form, online offerings. The results and findings are augmented with two additional supplementary questionnaires shared with the school participants immediately at the end of each school edition (in 2020 and 2021), which report on general course satisfaction.

The Computational DfAM Summer School

To contribute to disseminating DfAM principles to the next generation of designers, the Computational Design for AM summer school was conceived starting from the following premise: teaching DfAM means stimulating the creation of a design mindset ready to exploit the maximum potentialities of AM technologies in every phase of the process, from the idea generation to the post-processing. Hence, the summer school was conceived to train students and young researchers in exploring and applying the potential of computational-based strategies in DfAM through dedicated learning sessions and team working activities to create a problem-based learning context.

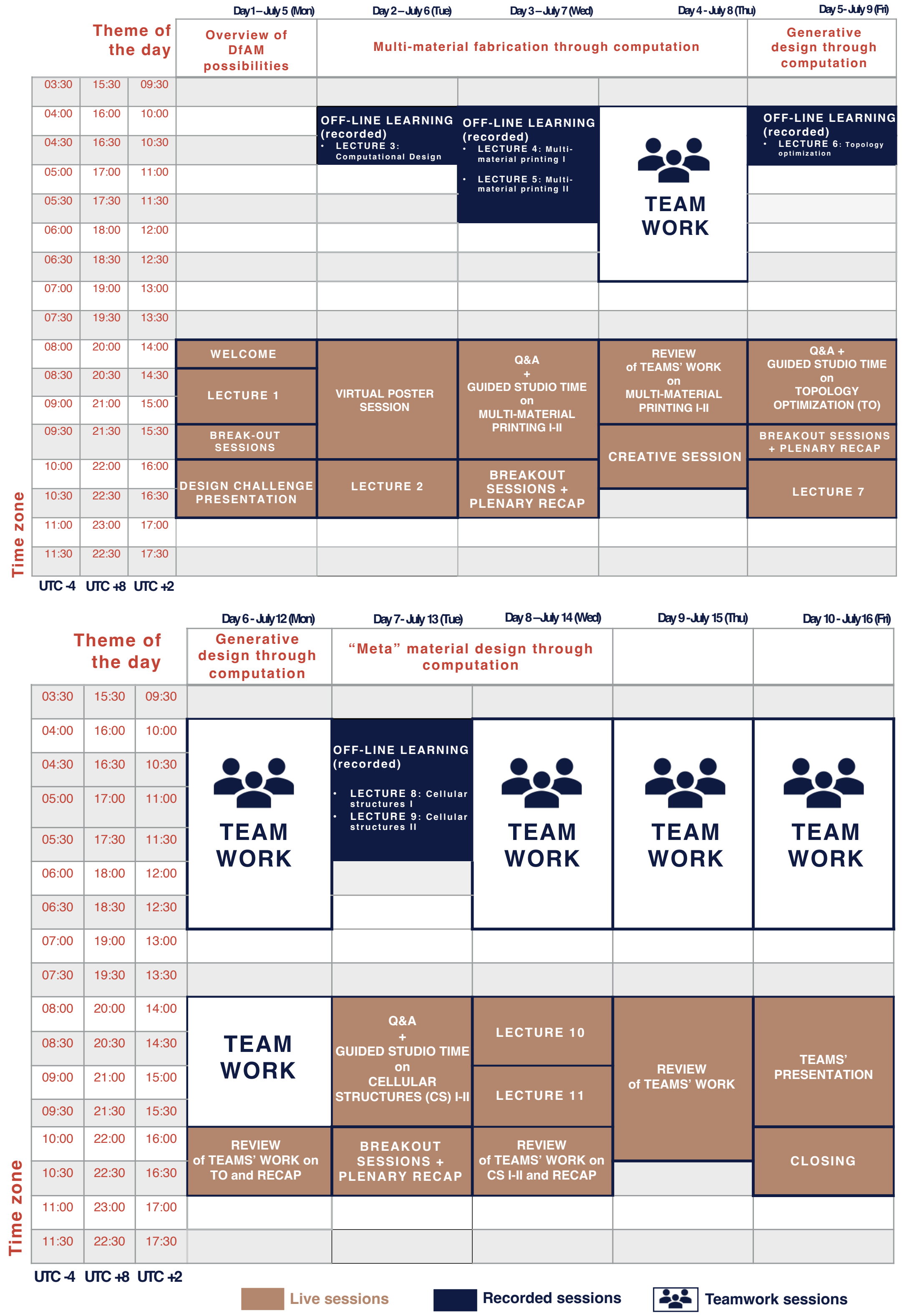
The following learning objectives were established: 1) explain the fundamentals and challenges associated with AM technologies and computational DfAM support methods; 2) apply the digital workflow (scanning-computational design-digital fabrication) for customized product design and state-of-the-art computational design tools and methods to DfAM; 3) identify appropriate and innovative application scenarios for AM.

The summer school was organized as an intensive two-week combination of lectures, teamwork, and project-based performance assessment (Fig. 1). In addition to the students from universities of the IDEA League alliance, the summer school involved students from the ASPIRE League (www.aspireleague.org), the Design Society (www.designsociety.org) as a worldwide community of researchers in the field of engineering design, and in 2021, students from Ashesi University in Ghana. Summer school participants were 34 in 2020 and 36 in 2021. For team working sessions, they were divided into groups of 5-6. Considering the broad relevance of AM technologies in multiple disciplines, students' backgrounds ranged from mechanical, materials, biomedical and aerospace engineering to industrial design and architecture. This heterogeneous mix of backgrounds was expected, considering the broad interest in AM technologies from different industrial fields and contributing to an added value for the school learning experience. In light of this heterogenous mix, a design challenge that could be addressed by all students independently from their background was conceived, as explained later in the text. Since the students' backgrounds were known before the beginning of the school, teams were organized to balance the knowledge and necessary skill sets, facilitate diversity, and manage teamwork hours with members in different time zones (Fig. 1). Indeed, each summer school edition has seen participants from at least two different continents. For example, the main criteria used are the following. We considered the gender balance, ensuring, when possible, that female participants in both editions were homogeneously distributed. For example, in the 2020 edition, 2 female members were included per team wherever possible. The second criterium was time-zone differences. In particular, we guaranteed that, for each team, only one student at most had a significantly different time zone to make the management of teamworking activities more feasible (e.g., the students could work in series). Where possible, we also avoided including too many students from the same university on each team. At the same time, we tried to achieve an equal distribution between students from PhD and Master programmes. It was also crucial that each team could count on at least a basic level of digital modelling, for example, by involving a team member with expected proficiency in using CAD tools based on the declared background.

In its online format, the summer school relied on Microsoft (MS) Teams as the communication environment, also serving as the course content management system. The teams were assigned to virtual rooms that could be visited by course instructors at any time during the school to initiate live discussions. During the school, groups organized themselves further into individual sub-teams with dedicated communication channels and meetings to facilitate the work over different time zones. The other means of communication include chatting over MS Teams and direct emails to course instructors.

The lectures were divided into four thematic blocks to cover core aspects of computational design for AM (Fig. 1). These blocks were: an overview of DfAM possibilities, multi-material fabrication, generative design, and metamaterial design. To facilitate the online teaching modality, the blocks were based on the flipped classroom approach as a combination of recorded sessions with lectures from the organizers and invited live talks from other researchers and experts in the AM field. Recorded lectures were made available to summer school participants about one week before the start. These lectures gave students the necessary background knowledge to be active participants during the related guided studio sessions, organized one for each of the four thematic blocks. This setup allowed students to receive immediate support and supervision for their projects by interacting informally with the course organizers. Since the summer school required the application of several computational tools, these guided studio times were also used for live tutorials, as well as explanations of programming scripts and solutions that were pre-prepared by the organizers to be used by the students during the school. Thus, students received direct support and live feedback from the course instructors during teamwork, breakout sessions, and guided studio times. At every school stage, at least two instructors were available to support the teams' work.

The central element of the summer school was the DfAM challenge, i.e., an open-ended design project introduced on the first day of the summer school (Figs. 1 and 2). In both instances of the summer school, the design challenge involved a redesign for AM of preselected parts and components of a bicycle. Students were asked to select at least one subsystem of the bike among those provided to them and implement the DfAM principles learned during the school. They were supplied with digital models of the following subsystems: the frame, the wheel, the seat post, and the fork with the front suspension. During the summer school, the participants learned the necessary theoretical background and skills required to solve the design challenge using computational methods and tools.



UTC -4	UTC +8	UTC +2	Day 1 – July 5 (Mon)	Day 2 – July 6 (Tue)	Day 3 – July 7 (Wed)	Day 4 - July 8 (Thu)	Day 5 - July 9 (Fri)
Theme of the day			Overview of DfAM possibilities	Multi-material fabrication through computation			Generative design through computation
03:30	15:30	09:30					
04:00	16:00	10:00		OFF-LINE LEARNING (recorded) • LECTURE 3: Computational Design	OFF-LINE LEARNING (recorded) • LECTURE 4: Multi-material printing I • LECTURE 5: Multi-material printing II	👥 TEAM WORK	OFF-LINE LEARNING (recorded) • LECTURE 6: Topology optimization
04:30	16:30	10:30					
05:00	17:00	11:00					
05:30	17:30	11:30					
06:00	18:00	12:00					
06:30	18:30	12:30					
07:00	19:00	13:00					
07:30	19:30	13:30					
08:00	20:00	14:00	WELCOME	VIRTUAL POSTER SESSION	Q&A + GUIDED STUDIO TIME on MULTI-MATERIAL PRINTING I-II	REVIEW of TEAMS' WORK on MULTI-MATERIAL PRINTING I-II	Q&A + GUIDED STUDIO TIME on TOPOLOGY OPTIMIZATION (TO)
08:30	20:30	14:30	LECTURE 1				
09:00	21:00	15:00					
09:30	21:30	15:30	BREAK-OUT SESSIONS			CREATIVE SESSION	BREAKOUT SESSIONS + PLENARY RECAP
10:00	22:00	16:00	DESIGN CHALLENGE PRESENTATION	LECTURE 2	BREAKOUT SESSIONS + PLENARY RECAP		LECTURE 7
10:30	22:30	16:30					
11:00	23:00	17:00					
11:30	22:30	17:30					

UTC -4	UTC +8	UTC +2	Day 6 - July 12 (Mon)	Day 7 - July 13 (Tue)	Day 8 – July 14 (Wed)	Day 9 - July 15 (Thu)	Day 10 - July 16 (Fri)
Theme of the day			Generative design through computation	"Meta" material design through computation			
03:30	15:30	09:30					
04:00	16:00	10:00	👥 TEAM WORK	OFF-LINE LEARNING (recorded) • LECTURE 8: Cellular structures I • LECTURE 9: Cellular structures II	👥 TEAM WORK	👥 TEAM WORK	👥 TEAM WORK
04:30	16:30	10:30					
05:00	17:00	11:00					
05:30	17:30	11:30					
06:00	18:00	12:00					
06:30	18:30	12:30					
07:00	19:00	13:00					
07:30	19:30	13:30					
08:00	20:00	14:00	TEAM WORK	Q&A + GUIDED STUDIO TIME on CELLULAR STRUCTURES (CS) I-II	LECTURE 10	REVIEW of TEAMS' WORK	TEAMS' PRESENTATION
08:30	20:30	14:30					
09:00	21:00	15:00			LECTURE 11		
09:30	21:30	15:30					
10:00	22:00	16:00	REVIEW of TEAMS' WORK on TO and RECAP	BREAKOUT SESSIONS + PLENARY RECAP	REVIEW of TEAMS' WORK on CS I-II and RECAP		CLOSING
10:30	22:30	16:30					
11:00	23:00	17:00					
11:30	22:30	17:30					

Figure 1: The summer school structure (2021 edition). It is based on the flipped classroom approach as an intensive two-week combination of: a) interactive live sessions involving lectures, guided studio

times, reviews and project-based performance assessment; b) recorded sessions made available one week before the summer school starts; c) teamwork. A "theme of the day" is identified for those days involving lectures, guided studio times and project reviews. The time zone difference is highlighted to make participants aware of this issue.

The challenge was addressed as a part of their practical work throughout the course. To facilitate the course, a design expert in the field of bicycle design served as a course instructor for the whole school duration. This expert has instructed participants concerning the main design requirements to be considered for redesigning these subsystems. As anticipated, considering the heterogeneous background of the participants, the bike design challenge was considered a topic general enough to be relatable by all participants, at least in the role of end-users.

Apart from the design challenge culminating on the closing day with final presentations of the designs produced by each team (Fig. 1), students were also asked to introduce themselves individually in a virtual poster session using a 30-second-long pre-recorded video. The breakout sessions also allowed students to share their intermediate outcomes with the course instructors and discuss other research and course-related topics.

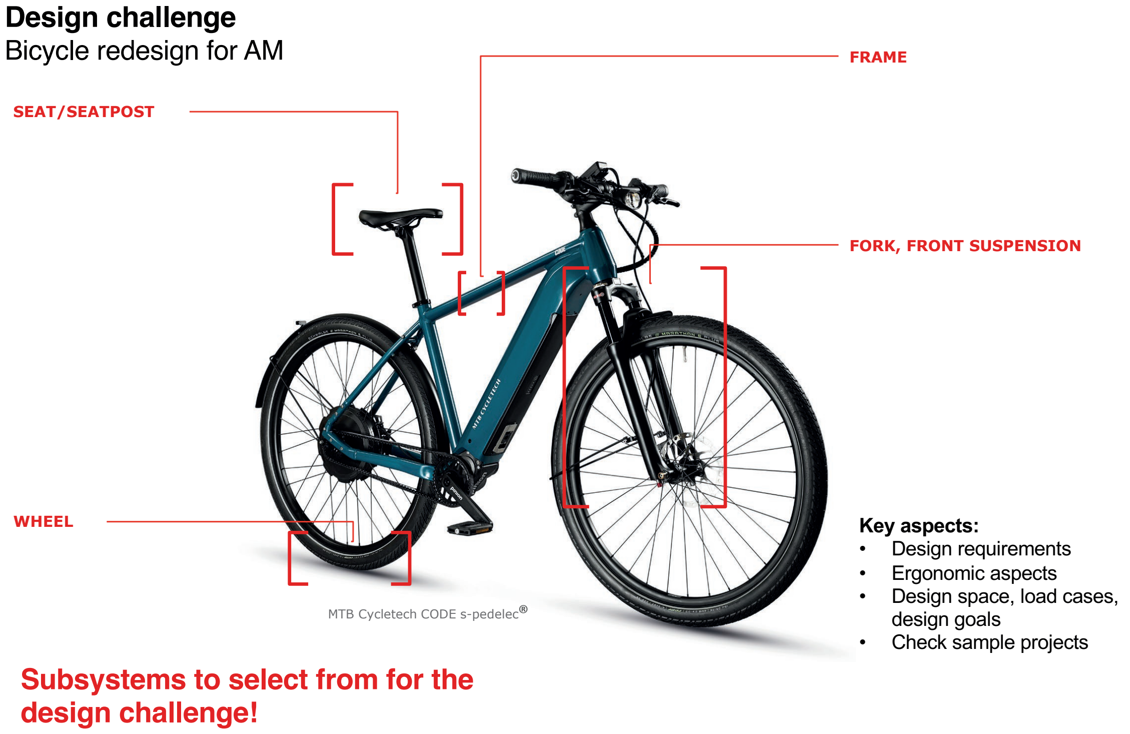


Figure 2: DfAM design challenge project showing the four possible subsystems of a bicycle students could select to be redesigned for AM.

The assessment is project-based and performed by all course instructors using 0-5 grading marks. Teams are evaluated for the quality of their presentation, innovativeness of the idea, printability and technical feasibility of the proposed solution, aesthetics and ergonomics (if applicable), and effectiveness of the implemented/foreseen design process. Given 6 evaluators (course instructors) and 5 categories, each team could score maximally 150 points. The three best teams were awarded a digital voucher from an international 3D-printing service.

Methodology

After completing the two summer school editions, the invitation for the follow-up questionnaire (for details regarding the questionnaire, please see Appendix) was disseminated to previous participants via email. The questionnaire implemented online using Microsoft Office 365 Forms focused predominately on (1) how their perceptions of the summer school have changed since their initial participation and (2) how the content from the summer school has or has not proven relevant for their work in the intervening years. This questionnaire consisted of 15 questions, with a mixture of quantitative, categorical, and free responses. Such a mixture of questions is characteristic of engineering design research to support studying various factors whose behavior would be difficult to characterize unless a combination of approaches is used (Blessing & Chakrabarti, 2009; Tashakkori et al., 1998). Thus, the obtained data allows us to capture the diversity of views among the participants in describing insights, opinions, and explanations regarding the summer school, with the possibility of obtaining unexpected results. The survey invitations were sent using the email addresses students used to register for the course each year and based on the email addresses provided at the end of each course by the students who wished to maintain long-term contact with the organizers. Additional email addresses were obtained using connections between alumni and the organizers through professional social networks.

In addition to the follow-up questionnaire, two supplementary questionnaires were prepared in 2020 and 2021 by the IDEA league for details regarding the questionnaire, please see Appendix). The questionnaires followed mixed question formulations similar to the follow-up survey and were disseminated via email. They were created to gain insights about various aspects of the summer school involving the individual lectures, contributions of practitioners/supervisors, design challenge and network building, and organization of the summer school (e.g., the online setup of the program, the balance between lectures and practices, course description). The rating was on a scale of 5, from “not at all satisfied” (1) to “extremely satisfied” (5). There were three open questions regarding: the most enjoyable part of the program, comments/suggestions for the design challenge, and comments/suggestions for improvement of the program. The survey invitations were sent to participants on the last day of the school using the email addresses students used to register for the course each year.

All the surveys were conducted anonymously, and the results are presented such that tracing individual answers to a particular survey participant is not possible. The research in this work has been approved by the ETH Zurich Ethics Commission.

Results

For the follow-up questionnaire disseminated to alumni of the summer school, a total of 23 responses were collected, denoting an approximate response rate of 33%. Participants were contacted via email or via social media. Responses rates were similar for each edition of the summer school, with 10 responses from participants from the 2020 version and 13 responses from participants from the 2021 version. Respondents were mainly at the PhD level of their studies (n = 57%), with other respondents from the MS (n = 22%), Postdoc (n = 9%), or Professional (n = 13%) levels. When asked about their initial motivation for joining the summer school, most respondents selected that they had a previous passion for AM that they wished to leverage in the summer school (n = 52%). Other respondents instead indicated that they were not already experts in AM and, as such, wished to use the summer school to gain these skills (n = 35%). Further, after completing the summer school, most respondents claimed that the program was either the most engaging online learning experience they have participated in (n = 43%) or similarly engaging compared to their other online experiences (n = 43%). Only 2 respondents selected that they felt unengaged by the online learning format of the summer school. Respondents who reported engagement with the content attributed it to (1) the practical and relevant nature of the topics being presented, (2) the responsiveness of the faculty, and, most commonly, (3) the inclusion of the group-centered design challenge. Students noted that the inclusion of the group work allowed them to interact with their peers in a way that may not often happen in online educational spaces. With respect to the course performance assessment, in 2020 the average score was 106.8/150 with the median of 105.5, whereas for 2021 the average performance was 112.4/150 with the median of 109.5.

Regarding the ultimate relevance of the summer school content, responses were relatively dispersed, with some participants saying that the AM topics from the school are relevant to projects they are currently engaged in (*n* = 39%), while others responded that the topics were relevant, but not being used in their current project (*n* = 26%). The remaining respondents believe that the topics are not currently relevant to their work (*n* = 26%). However, when looking into the future, respondents appear more optimistic, with 14 (61%) believing the topics from the summer school to be relevant to the long-term trajectory of their career. Seven respondents were unsure of future relevance, with only one respondent believing that the content was not relevant for their long-term career. In the follow-up open-ended question (yes, could you explain for which purpose (e.g. for career advancement, for future projects)?"), out 15 responses, 3 clearly indicated career advancement, while the reminder commented with either future projects or to obtain new skills in AM. When asked to assess the relevance of individual topics from the summer schools on a scale of 1-5 (5 being of most relevance), participants rated AM's overall design possibilities (i.e., "free complexity") the highest relevance with an average of 4.13/5. The design challenge was also viewed favorably with 3.57/5. More specific topics were viewed to be less relevant, including topology optimization with averages 3.30/5, lattice structures 3.22/5, and multi-material printing 2.70/5.

The supplementary questionnaires in 2020 and 2021 received 30 responses from 34 students and 31 responses from 36 students, respectively. The results for the closed questions sections showed that the rating of individual lectures was consistently high for all lectures, with an average of 4.44/5 (2020) and 4.45/5 (2021). The organization in both years was rated very positive as well, with the second run being rated somewhat higher. The questions regarding the organization and the rating in both years can be seen in Fig. 3.

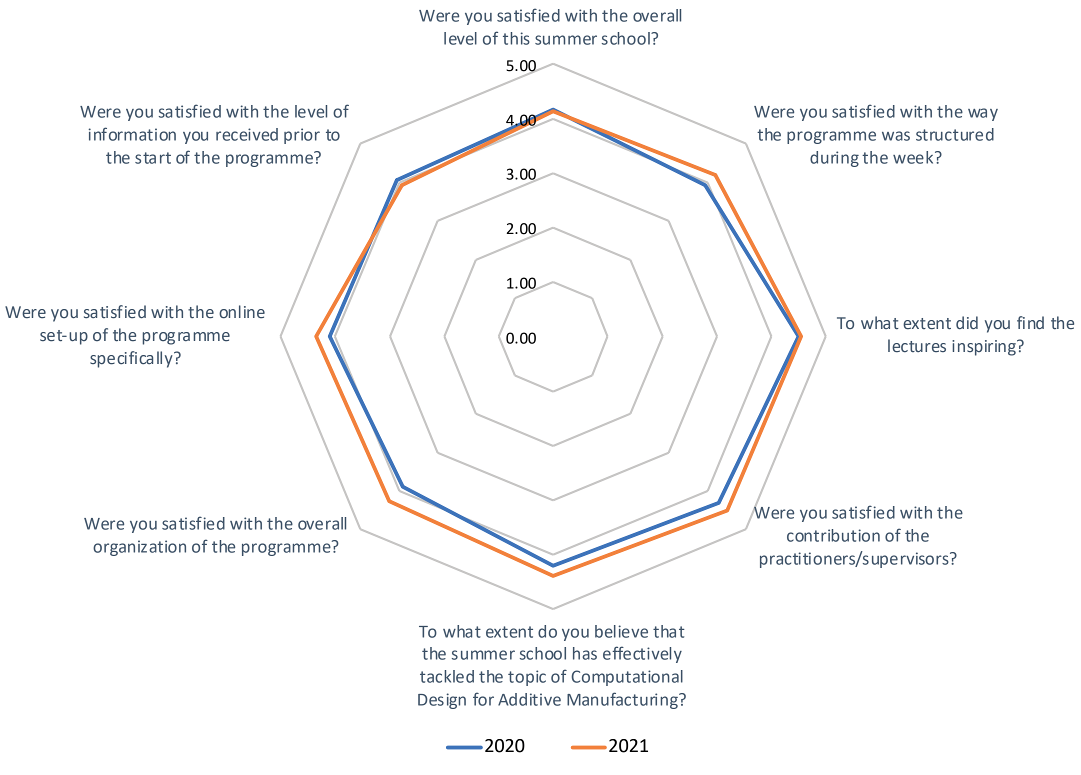


Figure 3: Responses for the closed questions sections of the supplementary surveys in 2020 and 2021.The results in the figure show the average value per question.

An important question is, “To what extent do you believe that the summer school has effectively tackled the topic of Computational Design for Additive Manufacturing?”. On this one, in 2020 and 2021, the average rating was 4.2/5 and 4.39/5, respectively. By responding to the question “How did you work for the design challenge? (a single-choice question, 1 to 5 scale, 1 - Always with my group and 5 - Always individually), the results for 2020 suggested the vast majority worked with a balance between individual and teamwork, 14 out of 30 students chose 3, and 12 students chose 2. Further, 2 students worked always with the team. The 2021 results spread over from 1 to 5, with slightly more towards 1 than towards 5. 7 out of 31 students worked always with the team, 5 students however worked always independently. In the open question regarding improvement of the program, one of the respondents who chose 5 (i.e. Always individually) showed frustration with the group forming. In contrast: in the open question about the most enjoyable part of the program, aspects that frequently appeared in the answers include: the variety of topics as well as the format of teaching, e.g., recorded and live lectures, meeting and working with people from other disciplines, and the design challenge (in particular the teamwork and as a practice of the theory). Students also frequently mentioned “new perspectives on AM”, “more information of the possibilities of AM”, “thinking about the design specifically for AM”, “the possibilities of AM at different scales”, “how these technologies/ knowledge can be used to design the parts”, “how to think for creating new designs”, and “new tools and software”.

Regarding the open question on improvements of the program, in both years, there were multiple comments and suggestions on tutorials for learning practical tools and software, regarding, e.g., topology optimization and parametric modelling of lattice structures. The frequent mention of practical tools and software suggests that the wish to learn practical tools was common among many students.

Other comments and suggestions touched upon, e.g., the design challenge and group formation, the prior knowledge for entering the summer school. The diversity of student backgrounds is common in master/PhD education. In the multi-disciplinary field of DfAM, this diversity becomes more pronounced. This was acknowledged by students as seen in the “most enjoyable parts”. Individual students who were less familiar with AM and computational design may have experienced more challenges in the program.

Discussion

A number of relevant insights can be derived from the questionnaires (i.e., the follow-up and the two supplementary ones). First, the fact that for a number of participants, some of the topics learned are not currently relevant in their professional careers was to be expected. Some industrial fields with a long tradition in computational design, such as the aerospace and biomedical industries, which attempt to utilize the design freedom enabled by AM beyond just streamlining their manufacturing, are more ready than others to adopt AM technologies (Prabhu et al., 2020). Indeed, this is confirmed by the survey participants working in architectural design stressing the immediate relevance of the topics learned for their careers. However, the fact that, overall, participants have seen the relevance of the learned topics from a long-term perspective means they understand the potential of the insights discussed. It is also worth noting that the instructors’ lectures, particularly those of the invited speakers, were intentionally strongly research-oriented, with a focus on the long-term implications of design. The idea was to make participants aware of the ongoing developments and wide range of possibilities that can be explored thanks to the design freedom allowed by AM technologies. Besides, since there were PhD students among the participants, a further aim was to provide them with suggestions for their research. Hence, although these insights may not be immediately relevant in a short-term scenario, especially in specific industrial fields, participants have instead caught their potential in a long-term view. This consideration matches appropriately with the other results obtained from the follow-up questionnaire. Indeed, the design challenge was considered relevant for their career because they may now be involved in team- project-based activities. On the contrary, the multi-material printing topic was considered less relevant than, for example, topology optimization because the former is still a pioneering field considering the reduced number of commercial printing technologies that can enable it. In general, we observe the trend that more specific topics were perceived as less relevant in favor of the design challenge, which also encompassed these topics to a certain degree but in the context of a specific design task. The affinity of students to participate in a concrete design challenge in AM, rather than specialized isolated topics, has also been recognized by others (Diegel et al., 2019): the complexity of the task that drives the course requires teamwork, hands-on experience, and application of a previously acquired knowledge, and contributes to the acceptance of project-based classes. Thus, framing specific topics more closely to the design challenge should increase their relevance for summer school participants. Similar findings to (Diegel et al., 2019) are reported in (Thomas-Seale et al., 2022) and (Williams et al., 2015) stating that students favor participation in hands-on environments in comparison to standard lectures. Most of the responses to the open-ended Question n°15 stress the importance of teamwork by stating that it boosted their motivation and allowed them to discuss and clarify the contents of the lectures. They also felt engaged in the design challenge and appreciated the fact that the set-up was based on real-life activities. These experiences correlate strongly with findings that informal learning environments that mimic real-life professional situations directly influence the knowledge created (Sawyer, 2005) and prove beneficial to reach the teaching outcomes of a DfAM project-based course (Williams et al., 2015).

Concerning the results of the supplementary questionnaires, an interesting aspect to highlight is that based on the open comments provided by the participants, a more practice-based program was expected with instructions on how to use specific software programs properly. Despite the clarification provided to manage this expectation in the second run of the summer school, this was still a request for a small number of students. Although practical indications were provided during the guided studio times, the limited time available was not enough to provide in-depth training on using a specific software tool to students with different backgrounds. Besides, the intention was to offer them an overview of the main tools available rather than concentrating the school only on one software platform. This decision was also taken because there is still not a unique, comprehensive platform to fully exploit the design freedom AM technologies provide. However, to limit this potential barrier to students' creativity, dedicated actions could be undertaken in future editions of the school, for example, by providing some pre-recorded tutorials. In this respect, it is also important to clarify once again that instructing participants on the use of a new software is not a priority in terms of learning objectives. As underlined, the priority is to show participants the solutions that could be developed now, and potentially in the future, thanks to the continuous innovations in 3D modelling tools for AM.

The supplementary questionnaires have also stressed several findings regarding the summer school. First, the average rating of 4.2/5 and 4.39/5 (in 2020 and 2021, respectively) regarding the question "To what extent do you believe that the summer school has effectively tackled the topic of Computational Design for Additive Manufacturing?" (Fig. 3), confirmed that the sub-topics covered in the summer school match the expectation of the students. Furthermore, the performance assessment of teams involving, presentation quality, idea innovativeness, printability and technical feasibility, aesthetics and ergonomics, and effectiveness of the implemented/foreseen design process achieving rather high average and median scores in both 2020 and 2021, confirm good adoption of relevant AM knowledge and skills. Second, the responses in the surveys also underlined the importance of creating a collaborative and multidisciplinary environment as a fundamental element for creating an engaging learning experience. With AM technologies, this multidisciplinarity is favored, considering how strongly interlinked design decisions are with those related to the material and the processing technologies. Hence, it is fundamental when planning an educational event focused on DfAM to promote the presence of a multidisciplinary audience. And third, in their responses, the students highlighted teamwork and networking as elements of the course they truly enjoyed.

They also stress the need to organize the teams with equal levels of multidisciplinary skills required to tackle the design challenge. In 2021, 5 students however worked always independently, and this indicates that 1 or 2 teams didn’t function a “team”.

Overall, the online modality has been demonstrated to limit students' engagement, even if the quality of the educational experience, thanks to the action put in place to stimulate teamworking, has moderately counterbalanced this issue. However, an aspect to underline concerning the online modality, particularly if compared to an in-person and residential modality, is that participants may have been distracted by other parallel obligations related to their daily activities, which may have prevented them from devoting themselves entirely to the program.

Conclusions

This paper aims to advance the knowledge concerning the education of the next generation of designers by discussing the insights collected from a two-edition online summer school on Computational Design for Additive Manufacturing. It describes the structure of the school and the primary educational targets considered as a reference to design the educational experience, from selecting the school's main topics to organizing the participants' teamwork.

Through the results collected from an online follow-up questionnaire and two supplementary questionnaires made available right after the end of each summer school edition, insights were derived starting from participants’ responses. Results show an overall positive evaluation of the offered educational experience for what concern the organization, the topics discussed and the participants' involvement. Specifically, the project-based approach has been demonstrated to be appreciated in the responses collected right after the school and in those collected from the follow-up questionnaire. It has indeed been considered a relevant experience also in a long-term perspective. Hands-on training is also an essential element of the learning experience. As the summer school focused on computational design aspects, more training on software applications was expected. Also, creating a multidisciplinary learning environment, i.e., enrolling students with different backgrounds, has been revealed to be a fundamental aspect of promoting knowledge contamination. This insight emerged from the analysis of the open comments provided by the participants. As a final consideration, the online modality has been essential in dealing with the impossibility of organizing in-person events. However, it is still considered not as engaging as the in-person modality.

We can conclude that, overall, the insight collected could be generalized and could thus be used to drive the design of similar educational experiences. This claim is supported also by the similarities identified with the relevant literature in the field. However, a higher number of respondents to the follow-up questionnaire would have further strengthened the potential use of feedback to improve future offerings of the school. To address this issue, the suggestion is to plan it in due time, which means alerting participants to make the collection of the responses more straightforward.

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Bibliography

Blessing, & Chakrabarti. (2009). *DRM, a design research methodology*. Springer Dordrecht.

Blösch-Paidosh, A. & Shea, K. (2021). Enhancing Creative Redesign Through Multimodal Design Heuristics for Additive Manufacturing. *Journal of Mechanical Design*, *143*(10). https://doi.org/10.1115/1.4050656

Blösch-Paidosh, A. & Shea, K. (2022). Industrial evaluation of design heuristics for additive manufacturing. *Design Science*, *8*. https://doi.org/10.1017/dsj.2022.8

Borgianni, Y., Pradel, P., Berni, A., Obi, M. & Bibb, R. (2022). An investigation into the current state of education in Design for Additive Manufacturing. *Journal of Engineering Design*, *33*(7), 461-490. https://doi.org/10.1080/09544828.2022.2102893

Diegel, O., Nordin, A. & Motte, D. (2019). Teaching design for additive manufacturing through problem-based learning. In *Additive manufacturing–developments in training and education* (pp. 139-149). Springer.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D. & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of engineering education*, *94*(1), 103-120.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S. & Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, *69*, 65-89. https://doi.org/10.1016/j.cad.2015.04.001

Greer, J. R. & Deshpande, V. S. (2019). Three-dimensional architected materials and structures: Design, fabrication, and mechanical behavior. *MRS Bulletin*, *44*(10), 750-757. https://doi.org/10.1557/mrs.2019.232

Leung, Y.-S., Kwok, T.-H., Li, X., Yang, Y., Wang, C. C. L. & Chen, Y. (2019). Challenges and Status on Design and Computation for Emerging Additive Manufacturing Technologies. *Journal of Computing and Information Science in Engineering*, *19*(2). https://doi.org/10.1115/1.4041913

Liu, J., Gaynor, A. T., Chen, S., Kang, Z., Suresh, K., Takezawa, A., Li, L., Kato, J., Tang, J., Wang, C. C. L., Cheng, L., Liang, X. & To, A. C. (2018). Current and future trends in topology optimization for additive manufacturing. *Structural and Multidisciplinary Optimization*, *57*(6), 2457-2483. https://doi.org/10.1007/s00158-018-1994-3

Montemayor, L., Chernow, V. & Greer, J. R. (2015). Materials by design: Using architecture in material design to reach new property spaces. *MRS Bulletin*, *40*(12), 1122-1129. https://doi.org/10.1557/mrs.2015.263

Prabhu, R., Miller, S. R., Simpson, T. W. & Meisel, N. A. (2020). Exploring the Effects of Additive Manufacturing Education on Students' Engineering Design Process and its Outcomes. *Journal of Mechanical Design*, *142*(4). https://doi.org/10.1115/1.4044324

Rosen, D. W. (2014). Research supporting principles for design for additive manufacturing. *Virtual and Physical Prototyping*, *9*(4), 225-232. https://doi.org/10.1080/17452759.2014.951530

Rosen, D. W. (2016). A review of synthesis methods for additive manufacturing. *Virtual and Physical Prototyping*, *11*(4), 305-317. https://doi.org/10.1080/17452759.2016.1240208

Sawyer, R. K. (2005). *The Cambridge handbook of the learning sciences*. Cambridge University Press.

Schauer, A. M. K., Fillingim, K. B., Pavleszek, A., Chen, M. & Fu, K. (2022). Comparing the effect of virtual and in-person instruction on students' performance in a design for additive manufacturing learning activity. *Res Eng Des*, *33*(4), 385-394. https://doi.org/10.1007/s00163-022-00399-8

Tashakkori, A., Teddlie, C. & Teddlie, C. B. (1998). *Mixed methodology: Combining qualitative and quantitative approaches* (Vol. 46). sage.

Thomas-Seale, L. E. J., Kanagalingam, S., Kirkman-Brown, J. C., Attallah, M. M., Espino, D. M. & Shepherd, D. E. T. (2022). Teaching design for additive manufacturing: efficacy of and engagement with lecture and laboratory approaches. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-022-09741-6

Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B. & Martina, F. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals*, *65*(2), 737-760. https://doi.org/10.1016/j.cirp.2016.05.004

Williams, C. B. & Seepersad, C. C. (2012). *Design for additive manufacturing curriculum: A problem-and project-based approach* In 2012 International Solid Freeform Fabrication Symposium, University of Texas at Austin.

Williams, C. B., Sturm, L. & Wicks, A. E. (2015). Advancing Student Learning of Design for Additive Manufacturing Principles Through an Extracurricular Vehicle Design Competition. ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.

Appendix

The Follow-Up Questionnaire

The follow-up questionnaire comprises 15 questions in total, and contains three different question types, namely a single- and multiple-choice questions, and open-ended questions. Questions 1-4 target general characteristics of the respondents to help interpret their answers in the reminder of the questionnaire in the context of their demographics. The motivation of a respondent to participate in the summer school as well as the relevance of the summer school for their future studies/ career are addressed in Questions 5-11. Investigation on the usefulness and purpose of the design challenge “Shapeways” prize for the summer school are addressed in Questions 12-13. The two questions target the respondents that received the award. Finally, Questions 14-15 compare the summer school to similar courses in which the respondents were involved during their studies:

1. Are you currently a master's student, a PhD candidate, a researcher/Postdoc or a professional? (*A single-choice question*)
    - Master
    - PhD candidate
    - Researcher/Postdoc
    - Professional
    - Other (*allowing the respondent to fill in a specific answer*)
2. If you are a professional for which industrial sector are you currently working? (*A single-choice question*)
    - Aerospace & Defense
    - Healthcare
    - Consumer goods
    - Transportation
    - Energy & Materials
    - Chemicals
    - Transportation & Mobility
    - Industrial Equipment
    - Consulting
    - Other (*allowing the respondent to fill in a specific answer*)
3. If you are a master's student, a PhD candidate or a researcher/postdoc, what is your current field of study or research? (*Open-ended question*)
    - *The respondent is asked to provide a written answer*
4. Which edition of the summer school did you attend? (*A single-choice question*)
    - 2020
    - 2021
5. What motivations have pushed you to apply to the Computational Design for Additive Manufacturing summer school? (*A single-choice question*)

- I have a passion for Additive Manufacturing technologies. It is my field of study or research.
- I was not an expert on Additive Manufacturing, and I wanted to know more.
- Other (*allowing the respondent to fill in a specific answer*)

6. After more than 1 year from the end of the summer school, do you believe that the topics learned during the summer school have been relevant for the projects/activities you are currently involved in? (*A single-choice question*)
    - Yes
    - Yes, but not for the current projects/activities I am currently involved in
    - No
7. If yes, could you explain for which purpose (e.g., for your thesis project, for your daily work in the company)? (*Open-ended question*)
    - *The respondent is asked to provide a written answer*
8. After more than 1 year from the end of summer school, do you believe that the topics learned during the summer school could be relevant for your career in the long term? (*A single-choice question*)
    - Yes
    - No
    - I am not sure (*allowing the respondent to fill in a specific answer*)
9. If yes, could you explain for which purpose (e.g., for career advancement, for future projects)? (*Open-ended question*)
    - *The respondent is asked to provide a written answer*
10. Considering the "Computational Design for Additive Manufacturing" subject of the summer school, are there any topics or activities that were not discussed/performed or were discussed/performed only marginally that, instead, you consider relevant? (*Open-ended question*)
    - *The respondent is asked to provide a written answer*
11. To what extend the following topics have influenced your career or your studies the most? (*Rate topics from 1 to 5 to denote lowest and highest relevance, respectively; one topic at the least, and all five topics at the most; a multiple-choice question*)

Relevance **Topic**	1	2	3	4	5
Multi-material printing					
Cellular/lattice structures					
Topology optimization/ generative design					
Design possibilities unlocked by Additive Manufacturing technologies					

The design challenge					

12. If you have received the Shapeways prize for the design challenge, did you find it useful and have you had the chance to use it? (*A single-choice question*)
    - Yes, I have used it
    - No, I have not used it
    - I won the prize, but never received it
    - I did not win the prize
    - Other (*in this special case the respondent can provide an elaborate written answer*)
13. If you have used it, could you please share with us for what you used it for (e.g., personal use, professional/research use) and for which product category? (*Open-ended question*)
    - *The respondent is asked to provide a written answer*
14. Compared to the other online learning experiences you have had the chance to attend or be engaged in (e.g., university courses, other summer schools), did you find the Computational Design for Additive Manufacturing properly engaging? (*A single-choice question*)
    - Yes, one of the most engaging learning experiences I have lived
    - It has been as engaging as the other learning experiences I have lived
    - I felt unengaged by the online modality and how the summer school was structured.
    - Other (*allowing the respondent to fill in a specific answer*)
15. Could you briefly explain why you felt engaged or not engaged (see Question 14) during the summer school? (*Open-ended question*)
    - *The respondent is asked to provide a written answer*

Supplementary Questionnaires

The structure for the two supplementary surveys on the teaching experiences, and students' feedback performed right after each summer school edition by the IDEA League.

1. Are you a master student or a PhD candidate? (*A single-choice question*)
2. Were you satisfied with the overall level of this summer school? (*A single-choice question, 1 to 5 scale*)
3. Were you satisfied with the way the programme was structured during the week? (*A single-choice question, 1 to 5 scale*)
4. Were you satisfied with the lecture of Lecturer No.# (*A single-choice question, 1 to 5 scale*)
    - This question is repeated for every lecturer involved with the course.
5. To what extent did you find the lectures inspiring? (*A single-choice question, 1 to 5 scale*)
6. Were you satisfied with the contribution of the practitioners/supervisors? (*A single-choice question, 1 to 5 scale*)
7. To what extent do you believe that the summer school has effectively tackled the topic of Computational Design for Additive Manufacturing? (*A single-choice question, 1 to 5 scale*)

8. Were you satisfied with the overall organization of the programme? (*A single-choice question, 1 to 5 scale*)
9. Were you satisfied with the online set-up of the programme specifically? (*A single-choice question, 1 to 5 scale*)
10. Were you satisfied with the level of information you received prior to the start of the programme? (*A single-choice question, 1 to 5 scale*)
11. Did you have time to build a network with fellow students? (*A single-choice question*)
    - Yes
    - No
    - Other (*allowing the respondent to fill in a specific answer*)
12. Were you satisfied with balance between the lectures and practices (including the design challenge)? (*A single-choice question*)
    - Yes
    - No
    - Other (*allowing the respondent to fill in a specific answer*)
13. Do you have any comments/suggestions concerning the design challenge? (*An open-ended question*)
14. Were you satisfied with the set-up of the design challenge? (*A single-choice question, 1 to 5 scale*)
15. How did you work for the design challenge? (*A single-choice question, 1 to 5 scale, 1 - Always with my group and 5 - Always individually*)
16. Would you recommend that other fellow students to take part in a such programme? (*A single-choice question*)
    - Yes
    - No
    - Other (*allowing the respondent to fill in a specific answer*)
17. What did you enjoy most about the programme? (*An open-ended question*)
18. Do you have any suggestions or comments for improvement of the programme? (*An open-ended question*)