International Journal on Interactive Design and Manufacturing (IJIDeM) (2020) 14:1305–1319
https://doi.org/10.1007/s12008-020-00697-2

ORIGINAL PAPER

Usefulness of prototypes in conceptual design: students' view

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Received: 27 September 2019 / Accepted: 28 August 2020 / Published online: 12 September 2020

Abstract

Planning prototyping strategies for conceptual design purposes is a crucial activity, which needs a clear understanding of the potentialities of the different typologies of prototype. Therefore, to prepare future designers, it is very important to provide the required information in design-related academic courses. However, prototypes and prototyping activities are often taught in specific courses with a major emphasis on the underpinning technologies, but with limited attention on design implications, especially about the fuzzy-front-end of the design process. The work presented in this paper aims at investigating about how students perceive the usefulness of prototypes during conceptual design activities, in order to provide first indications about the gap to be filled. To this purpose, two classes of students participated to an experimental session, and were asked to perform a conceptual design task individually. Subsequently, they participated to an on-line survey developed to gather information about the perceived usefulness of prototypes, in relation to the performed conceptual design activity. Several findings have been obtained from this work, but maybe the most impacting one concerns the different consideration that the two samples of students had about the fidelity of prototypes. Indeed, differently from what recently highlighted in current literature, it emerged that engineering students preferred low-fidelity prototypes. However, other unexpected evidences have been found, which highlight that at least for the considered institution, students still lack a comprehensive understanding of the design-related potentialities of prototypes.

Keywords Prototyping · Design · Design education · CAD · Additive manufacturing · Engineering education

1 Introduction

The increasing evolution of prototyping technologies offers many different alternatives to designers. However, the identification of the optimal prototyping strategy to support the design phases is still a critical and complex activity, involving a number of different aspects [1]. Consequently, it is not surprising that students find non negligible difficulties in elaborating prototyping strategies [2]. However, while it is possible to highlight the differences between novice designers (e.g. students) and expert designers in the use of prototypes during the design phases [3], general guidelines have not been defined so far. In fact, different prototyping cultures exist in industry [4], and any design task is somehow a particular case, also depending on the specific design phase. Moreover, non-negligible differences about the use of prototypes have been observed between engineering and industrial design students [5]. The problem is even worsened by the ethnological differences that can exist among different didactical contexts, which increase the heterogeneity of the potentially available data to be analyzed. Therefore, to ensure a comprehensive and updated training to students, it is important to collect information about how they perceive the usefulness of prototypes when accomplishing a given design task.

Focusing the attention on the conceptual design phase (which is acknowledged to be crucial for the final product success), the present work aims at investigating a class of MSc Engineering students and a class of MSc Industrial Design students from the University of Florence (Italy). In particular, the main objective of the investigation is the identification of possible differences about how the two kinds of students perceive the usefulness of prototypes for conceptual design purposes.

A specific methodological procedure has been developed, where students are asked to perform a specific conceptual design activity, and then are asked to participate to an on-line survey. The methodological procedure is described in Sect. 3, after a short literature review about previous attempts

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to gather design and prototyping-related information from students (Sect. 2). Section 4 introduces the considered samples and shows the most impacting results which have been highlighted in this specific case study. Then, comprehensive discussions and conclusions are shown in Sect. 5.

2 Background

2.1 Definitions, parameters and roles of prototypes

2.1.1 Definitions of the term "prototype"

Although prototypes and prototyping activities are largely acknowledged by scholars and industrial practitioners, the meaning of these terms is still not standardized, and is characterized by several and non-trivial aspects. For example, Ulrich and Eppinger [6] defined a prototype as "an approximation of the product along one or more dimensions of interest" and the prototyping activity as "the process of developing such an approximation of the product". However, also more restrictive views exist, such as that of Ullman [7], who considers "a prototype" any "physical model" representing products. But, also more general definitions exist, like that of Houde and Hill [8], who defined prototype "as any representation of a design idea, regardless of medium" and considered a designer as "anyone who creates a prototype in order to design". Actually, other definitions and classifications can be found in literature (e.g. [9–13]), as confirmed by the literature review performed by Jensen et al. [14]. However, providing an exhaustive review of definitions falls out the scope of this work, where it is sufficient to consider a definition of prototype, which is capable to clearly distinguish physical ones from virtual ones. Accordingly, taking inspiration from the recent work of Lauff et al. [15], we consider a prototype as a "a physical or digital embodiment of critical elements of the intended design [...]".

2.1.2 Parameters involved in the prototyping activities

Actually, the original definition provided by Lauff et al. [15] also includes aspects related to the roles (i.e. what we are prototyping for) and the prototyping technique (i.e. iterative), but due to the nature of the work described in this paper, it is necessary consider a more general view, i.e. not specifying roles and techniques. Indeed, while the definition of Lauff et al. [15] explicitly mention the adjective "iterative", also the parallel prototyping technique exists. Additionally, [16] highlighted other techniques, such as subsystem isolation, requirement relaxation, scaled prototyping and virtual prototyping. Consequently, since the objective of this work is to provide a framework for investigating the actual understanding that students have about different aspects of prototyping, it is necessary to consider the various alternatives (where possible).

Besides the parameters involved in some of the prototyping techniques mentioned above (i.e. scale, subsystem decomposition, and the nature of the prototype), another important parameter is that of Fidelity. Virzi [17], by taking inspiration from the Turing test, defined High-Fidelity prototypes (which cannot be easily distinguished from the final product) and Low-Fidelity prototypes (which can be rapidly distinguished from the final product). This definition, like other ones available in literature [8, 18–20], considers Fidelity as a measure of the "closeness" between the prototype and the final product. Although this generic definition has been successfully used in many research works, some scholars felt the need to provide more focused meanings. For example, MC Curdy et al. [21] identified five "dimensions" of Fidelity, together with an intermediate level (mixed fidelity). More precisely, the identified dimensions concern the fidelity of data, functionality, interactivity, form/visualization, and performance. However, other Fidelity dimensions can be found in literature. Indeed, Mathias et al. [22] considered the realization process, Bao et al. [23] mentioned the material type, while Sauer et al. [24] referred to the fidelity of the testing situation. However, for the scope of this work, it is not possible to discern the different fidelity types, because of the impossibility to retrieve sufficient information from an on-line survey. Moreover, aspects related to the different dimensions of Fidelity still need to be investigated in deep by scholars [25].

Therefore, we consider here the more general and well acknowledged definition of Virzi [17], between high-fidelity and low-fidelity prototypes. Nevertheless, according to Jensen et al. [26], the functionality of the prototype is an important parameter to be considered, especially in early conceptual design phases. Therefore, we considered also this parameter in our study.

2.1.3 The roles of prototypes

Prototypes are acknowledged to be often used for communicating, exploring, refine and evaluate design outcomes [27–30], and also to gather user feedbacks [31]. Accordingly, Ulrich and Eppinger [6] reported that prototypes can be used for "learning" about product functioning and/or the satisfaction of customer needs, for "communication" with the different subjects involved in product development, as "Integration" to verify that components and subsystems work as expected, and as "milestone", i.e. the possibility to demonstrate the progress of the product development process. Another point of view about the roles of prototypes is provided by Paderno et al. [32], who mention "Design, Representation, Experimentation and Communication".

However, other roles have been identified by scholars, concerning more detailed aspects related to physical hardware or even focusing on educational aspects [33]. For example, when referring to drawings and solid models, Ullman [7] listed seven different roles for prototypes, i.e. archive the geometric form, communicate ideas (e.g. for selection purposes [34]), support analysis, simulate the operation of the product, check completeness, support problem-solving process, and act as a synthesis tool. Accordingly, also Kelley and Littman [35] asserted that "prototyping is problem solving", and some researchers actually point out that using prototypes in early conceptual design phases could help designers in visualizing and solving problems [36, 37]. However, the effect of prototyping on design fixation [38–40] has not been comprehensively defined, and is currently under investigation by scholars (e.g. [41–45]). In any case, the mentioned debate concerns detailed issues related to the "exploration" of the design spaces (intended as problem space, solution space [46]), which fall out of the scope of the work presented in this paper.

According to Camburn et al. [16], the following set is composed by the most recurring and acknowledged roles (or objectives) attributed to prototypes:

- Exploration, i.e. supporting the process of searching new design concepts or ideas.
- Active learning, i.e. supporting the process of gaining new knowledge about the design space and/or relevant phenomena.
- Refinement, i.e. supporting the process of gradually improving the design.
- Communication, i.e. supporting the process of sharing information about the design, with different stakeholders.

2.2 Prototyping-related surveys and interviews with students

The use of questionnaires for investigating around design related issues is acknowledged and diffused from years (e.g. [47]). Accordingly, the interest toward the use of prototypes in design processes, led scholars to perform many investigations where, for some of which, surveys and/or interviews have been used in order to gather information from industrial practitioners and/or students (e.g. [3, 5, 15, 48–51]). Focusing on students-related contributions where information have been explicitly extracted about the use of prototypes, the following paragraphs show the items found in the literature review performed for this work.

Lauff et al. [48] recently performed a pilot study including surveys and interviews, where both students and professionals have been involved. In particular, surveys where composed by eight questions for students, and twelve for professionals, mainly about the meaning of the term "prototype", the purpose of prototyping, pros and cons of prototyping. Among the obtained results, the authors highlighted that while both students and professionals agree that prototypes can be useful for testing functionality of concepts, students rarely mention the possible use of prototypes for communication, decision making and learning. In the same year, the work of Deininger et al. [3] has been published, where semi-structured interviews have been used to collect data about how novice designers (students from a capstone engineering design course) use prototypes. The results confirm that students perceive prototype as a tool for testing and evaluating functionality of concepts, but differently from what observed by Lauff et al. [48], all participants reported that prototypes have been used in their project for communication purposes.

Böhmer et al. [49] performed an investigation about how students use physical prototypes, the effect of prototyping in their design thinking process, and what affects prototyping results. The considered sample of students was from a Mechanical Engineering Design and Manufacturing course, and the methodological approach included two intermediate online surveys and a set of interviews with a thirteen subjects. The obtained results showed that a single prototype is not enough for comprehensively support the design process, but also that more prototypes can even be detrimental. The authors concluded that it is fundamental to train students in developing a correct prototyping strategy, in order to make them capable to efficiently exploit the potentialities of prototypes.

Koohgilani et al. [50] used a basic quantitative and qualitative online questionnaire in order to gather information about the students' and practitioners' views of the use of rapid prototyping techniques in place of traditional ones. The sample of convenience included Product Design students, academics and also design professionals from the Dyson Ltd. Among the obtained results, concerning what should be taught in design courses, it emerged only a slight preference toward rapid prototyping techniques. Moreover, the Head of Design at Dyson reported that only traditional prototyping skills should be taught, because rapid prototyping ones can be learnt during the professional career.

Even if not used as main investigation tools, surveys and/or interviews have been often used by researchers in order to find preliminary or additional data. For example, questionnaires to students were administered in order to identify the major difficulties perceived by students in project-related mechanical design courses [2]. Among the results from the mentioned contribution, it emerged that prototyping activities are perceived as difficult ones, when working within time and budget constraints. In particular, one of the hardest task appeared to be that of developing a feasible prototyping strategy.

Also in the work of Greenhalgh [52], the survey has been used as a secondary research tool, but was used to understand students' perception about the different techniques for constructing prototypes. The sample of students came from four courses of interior design, and among the various results, it has been highlighted that the construction method to build the physical prototype (hand-made or 3D printed) influenced the students' designs.

Interviews have been used also in the work of Yu et al. [5], in order to investigate the differences between industrial designers and engineers. It was dedicated to industrial professionals, while additional information was retrieved from both engineering students and industrial design students, by means of prototyping workshops. One of the most interesting results emerged from this study, is that while engineers tend to use prototypes for testing purposes, industrial designers are more willing to use them for exploratory purposes. Moreover, and maybe as a consequence of that, while engineers often adopt high fidelity prototypes, industrial designers largely exploit rough low fidelity prototyping.

2.3 Current lacks and motivation

The reviewed literature contributions highlight that the development of a prototyping strategy, as well as the identification of the most suitable prototype, are critical activities of product design process and development. Unfortunately, the complexity of the argument and the presence of conflicting observations (e.g. concerning the use of prototypes for communication purposes), make it impossible to provide shared and easy-to-learn instructions. Therefore, students from design courses (e.g. from Industrial Design and Engineering Design), may have some difficulties in understanding the actual potentialities of prototypes, especially in the fuzzy-front-end of the design process. This can be a crucial issue for the academic development of future designers, because without a clear understanding of students lacks, it is not possible to comprehensively provide them the required information.

In the attempt to shed further light on the actual understanding that students have about the role of prototyping in design, it is fundamental to investigate on the usefulness that they perceive about prototypes. This kind of information is expected to allow the identification of new opportunities for improvements on both didactical and research purposes. Unfortunately, as far as the authors know, there are not research works focused on this specific argument.

To provide a first attempt to fill such a gap, the work described in the following sections focuses this kind of investigation on the most creative and critical phase of the design process, i.e. the conceptual design phase.

3 Methodological approach

The investigation approach encompasses the following steps:

- Step 1: Administering a conceptual design task to one or more samples of students.
- Step 2: Performing an on-line survey.
- Step 3: Post-processing the set of gathered data.

The following subsections report a brief description of each mentioned step.

3.1 Administering the conceptual design task

To allow students focusing on the peculiar activities related to the conceptual design task, the easiest way is to make them working on a specific one. In this way, it is possible to avoid possible misunderstandings about the actual meaning of "conceptual design". Moreover, by administering the same task to the entire sample, it is also possible to ensure that all students are aligned in terms of complexity of the considered design problem.

The design task is administered by following few simple instructions:

- Introduce the design task and the related context.
- Provide a list of design requirements.
- Ask for a sketch of the preferred concept.
- Collect the generated concepts.

The time allotted for performing the design task can vary, depending on the available didactical resources. In any case, for the purposes of this investigation, one hour can be acceptable. Indeed, the administered task is intended only to provide a common target to the sample. Details about the characteristics of the two samples considered in this study are provided in Sect. 4.

The considered design task was the design of a professional ladder, according to the following main instructions:

> A firm desires to challenge into the market of professional ladders, which unfortunately is already full of different product variants. Suppose you are the designer appointed to propose an original solution, according to the following requirement list. Try to generate solution that differ as much as possible from those already available (see the provided examples).

The requirement list (Table 1) has been compiled according to the well-acknowledged checklist of Pahl et al. [53]. Please see the "Appendix" for the provided examples about the existing professional ladders. Students were allowed to use their multimedia devices to perform searches in the World Wide Web.

3.2 Performing the survey

Descriptive surveys are can be used to collect information about the phenomenon to be investigated [54], by reporting

Table 1 Design requirements list

Geometry	Minimize the size when not used
	Maximum extension = 4 m
	Maximize the adaptability to the different stand conditions
	Maximize the number of the different geometrical configurations of the ladder
Forces	The ladder must support 250 kg in each of its possible configurations
	The ladder must resist to falls from four meters
Safety	Maximize the stability and the adherence of the supports
Material	Use only fireproof and corrosion-proof materials
Use	Minimize the operations required to pass from the non-use condition to the in-use condition
Ergonomic	The maximum weight of the ladder is 10 kg
	When in non-use condition, the ladder must be easily transportable by a single person
Maintenance	Ease the maintenance operations
	Eliminate or minimize the need of lubricant
Production	Production batch of 1000 pieces/year
Costs	Maximum allowable cost for the firm = 30€/piece

factual data or opinions that can lead to more comprehensive studies [55].

It is also important to discern between cross-sectional studies and longitudinal studies [56]. In the first, the data are collected within a single and relatively short time period, while the longitudinal studies collect data at more than one point in time (even across multiple years). Due to the time limits imposed by the considered academic courses, the cross-sectional study was the obvious choice.

Then, to formulate the questions, the most acknowledged parameters have been considered [54] (e.g. Reliability, Response rate, Relevance, etc.), by following suggestions and guidelines available in literature [55, 57].

Therefore, in this work prototypes have been subdivided in two main families, i.e. virtual ones and physical ones. CAD, CAE, Rendering, Virtual reality and augmented reality have been considered as tools for building virtual prototypes. Differently, handcrafting, additive manufacturing, subtractive technologies and "on-the shelf" constructions (e.g. Lego building blocks or Meccano parts), have been considered as different methods to build physical prototypes.

The structure of the survey is schematically shown in Fig. 1, together with a shortened version of the related questions. Only closed-answers are considered in this investigation, in order to mitigate the possibility of mismatching answers from students. However, for few questions, an additional open answer has been provided to allow participants to indicate possible alternative options.

As shown in Fig. 1, the survey includes questions about the prototype typology, the roles of prototypes, their functionality, the decomposition level of prototypes, their scale, and the audience expected for them.

Concerning the roles of prototypes (involved in Questions 7, 8 and 9 of Fig. 1), they are acknowledged to be often used for communicating, exploring, refine and evaluate design outcomes [27–30], and also to gather user feedbacks [31]. Accordingly, we considered the set of roles listed by Camburn et al. [16]:

Exploration, i.e. supporting the process of searching new design concepts or ideas.

Active learning, i.e. supporting the process of gaining new knowledge about the design space and/or relevant phenomena.

Refinement, i.e. supporting the process of gradually improving the design.

Communication, i.e. supporting the process of sharing information about the design, with different stakeholders.

Concerning the possible options to answer Question 16 (see Fig. 1), the considered stakeholders have been identified by a brainstorming session, where the authors identified the most recurring subjects that (based on their experience) can be somehow involved in conceptual design tasks.

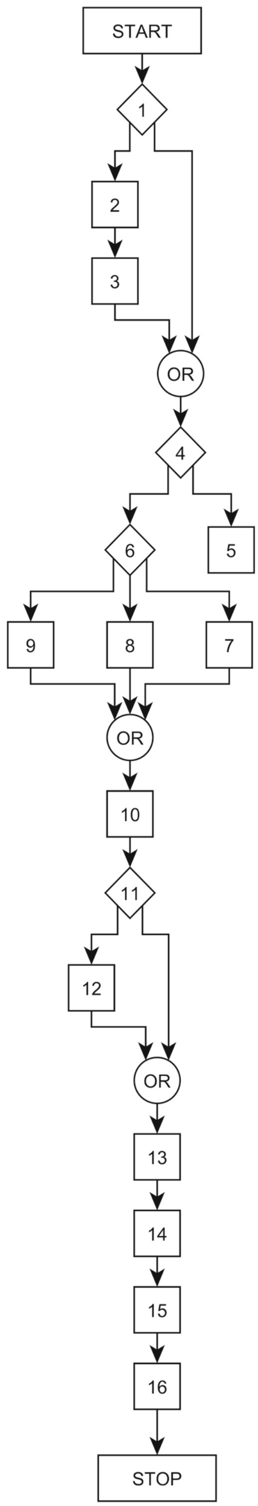
3.3 Post-processing the gathered data

After collecting the answers, data are exported in a MS Excel worksheet to perform more comprehensive analysis. Representation types and possible statistical analysis depend on the type of results that researchers are willing to search for, and it is not possible to provide a generalized procedure. However, focusing on the investigation performed in this work, where two different samples of students have been analyzed, the main results to be observed consist in the differences among the provided answers. In this case, graphical representations should be used, which allow to rapidly visualize the most evident differences. Moreover, where differences are identified, non-parametric statistical tests can be performed (e.g. Chi-square tests) to verify the reliability of the observed results.

4 Results

Engineering students and Industrial Design students form the two considered samples, both belonging to courses from the first year of the related Master of Science degrees. According to the official study programs, the two classes of students had not participated to courses specifically focused on prototyping and/or additive manufacturing technologies. Moreover, the investigation has been performed within the first three days of the two courses to avoid any contamination to the actual knowledge of students about these arguments.

In particular, 52 Engineering students and 47 Industrial Design students composed the two distinct samples. To



Question number	Question content and short description
1	Have you ever heard about prototypes before today?
2	Please select the prototypes that you know *[it is possible to select different types of prototypes among virtual and physical ones].*
3	In which context have you seen these prototypes? *[the following options are available: at school; at work; free time; other]*
4	When performing the assigned design task, have you felt the need for any kind of prototype (beside sketching)?
5	Why in your opinion, prototypes aren't useful for performing the assigned task?
6	For which family of prototype did you feel the need? *[the following options are available: virtual, physical and both]*
7	Please indicate which physical prototype did you intend to use for each specific role *[a matrix with multiple selectable options is provided. Rows represent the possible roles of prototypes, and columns represent the different prototypes alternatives for the selected family]*
8	Please indicate which virtual prototype did you intend to use for each specific role *[a matrix with multiple selectable options is provided. Rows represent the possible roles of prototypes, and columns represent the different prototypes alternatives for the selected family]*
9	Please indicate which virtual prototype did you intend to use for each specific role *[a matrix with multiple selectable options is provided. Rows represent the possible roles of prototypes, and columns represent the different prototypes alternatives for the both the families]*
10	Please indicate in which way did you intend to exploit the prototypes *[the possible options are: by realizing different prototypes in parallel; by realizing gradually updated prototypes in series; in a mixed way]*
11	Your prototypes were intended to be fully functional, static, or a mix of them? (Please select one of the three options).
12	Functional performances are intended to be proportional to the scale of the prototype?
13	Please select the scale at which did you intend to build your prototypes. *[the following options are available: 1:1; augmented; reduced; not in scale; multiple scales considered]*
14	Please select the decomposition level of your prototype. *[the following options are available: all the product; part of the product; not a part of the product; multiple decomposition levels]*
15	How much your prototypes resemble the final product?. *[the following options are available: with high fidelity; with low fidelity; I considered both the fidelity levels]*
16	Please indicate the stakeholders with which your prototype was intended to interact. *[the following options are available: myself; teacher; final users; vendors; suppliers; management; technicians; other designers; other (please specify)]*

Fig. 1 The structure and the contents of the survey

ensure the uniformity of the input data, the same examiner performed the investigation in the same way for the two classes.

A short presentation of the design task (designing an innovative professional portable ladder) has been performed by means of few slides (a presentation of about ten minutes per class), and two paper sheets have been administered to each

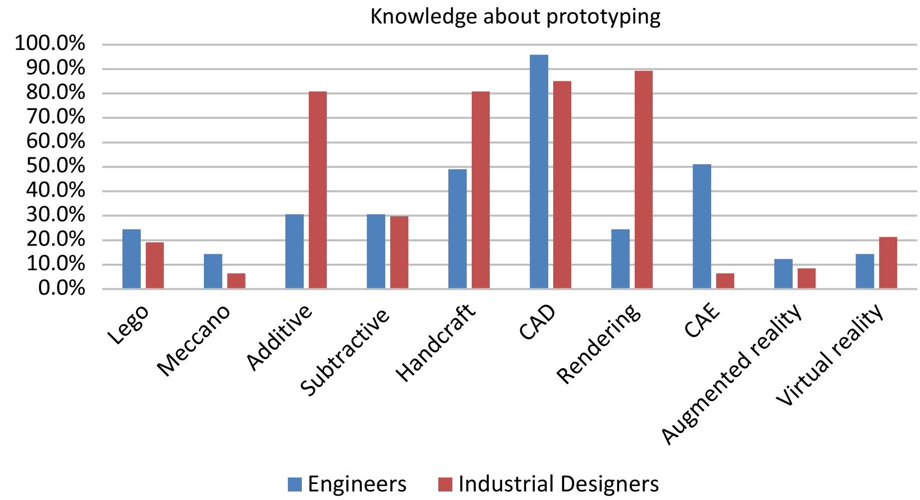


Fig. 2 Students' background about prototyping technologies

student, where data about the design task was reported (task description, list of design requirements and few images of current ladder variants taken from the internet).

Then, after the conceptual design task, a short presentation has been shown to both classes (fifteen minutes), about the different types of prototypes (images and verbal descriptions).

The time allotted for performing the design task was 1 h as well as the time allotted for the survey. However, all students (in both the two classes) completed the survey within 40 min.

In the following subsections, the main results from the performed survey are exposed.

4.1 Students' background

Concerning the background of students, the survey highlighted non-negligible differences about the knowledge of certain prototyping technologies (Fig. 2). A Chi-square test has been performed (nine degrees of freedom, p-value = 0.05), to confirm that the two samples are actually different (calculated chi-square > than critical chi-square). Nevertheless, some of these differences were somehow expected, due to the natural dissimilarity between the two study programs. For example, it was expected that industrial designers could have more confidence with handcrafted models and renderings, and it was expected as well that engineers could have more knowledge about CAE tools (e.g. Finite Element Analysis).

However, the difference observed about the background knowledge of additive manufacturing technologies for prototyping purposes, was not expected. In fact, although the two samples had not any specific course about additive manufacturing in their study programs, Industrial Design students declared a higher knowledge on this topic.

4.2 Perception of the usefulness of prototypes

The answers to Question 6 (see Fig. 1), allowed to highlight non-negligible differences about how the two samples perceived the usefulness of prototypes for the performed conceptual design task. Indeed, as shown in Fig. 3, while both the samples almost equally selected "physical prototypes", industrial designers seemed to feel less comfortable with the use of "only" virtual prototypes. Instead, they seemed to largely prefer a conjoint use of both virtual and physical prototypes (60% of industrial designers selected this option, against only the 31% of engineers). A Chi-square test has been performed (two degrees of freedom, p-value = 0.05), confirming that the observed percentages are actually influenced by the considered class of students (calculated chi-square > than critical chi-square).

4.3 Roles of prototypes VS prototyping technologies

Answers to questions 7, 8 and 9 (see Fig. 1), led to detailed information about how students felt the need to use prototypes, and which of them were preferred. Focusing the attention on roles only, no meaningful differences were observed about how engineers and industrial designers considered all the roles indicated in Sect. 3. But considering the analysis of the specific technologies vs the specific roles, some observations can be performed. To this purpose, results shown in Fig. 4 have been obtained by summing the answers from virtual [physical] prototypes selection in Question 6, with those concerning virtual [physical] prototypes from the "both" option. In this way, all students actually perceiving the usefulness of virtual [physical] prototypes have been considered. According to the performed chi-square tests (p-value = 0.05, four degrees of freedom for the "virtual" group of answers, and three degrees of freedom for the "physical" one), the two classes of students behaved differently only for

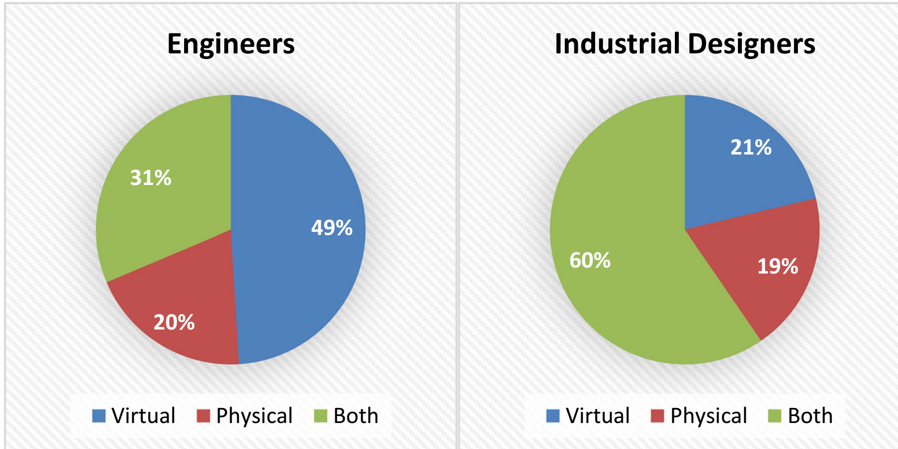


Fig. 3 Pie charts representing the students' perception about the typologies of prototypes that could be useful for the performed conceptual design task

virtual prototypes. Among this group, Fig. 4 shows that concerning the role "communicate", although engineers declared a bigger knowledge about CAE tools (see Fig. 2), they do not consider them for communication purposes. Except for small differences about the consideration of virtual reality and augmented reality, there are not unexpected differences in the "virtual" group of graphs shown in Fig. 4.

Concerning students that selected physical prototypes, the chi-square test revealed that the null hypothesis (i.e. the observed results are not dependent on the considered sample of students) cannot be rejected. Therefore, differences like that for the "communicate" role (e.g. for "handcraft" prototypes) cannot be validated here. However, some of them are somehow expected, due to the different didactical backgrounds of the two classes. Nevertheless, for the "refining" role, within physical prototypes, engineers seemed to find less usefulness in additive manufacturing technologies when compared with industrial designers.

4.4 Fidelity levels considered by students

Analyzing the answers from Question 15 (see Fig. 1), it emerged that while no substantial differences can be observed among the two classes for high-fidelity prototypes, a bigger part of engineering students seemed to perceive the need for low-fidelity prototypes (see Fig. 5). The statistical reliability of the differences among the two samples, in terms of Fidelity-related answers, has been confirmed by a chi-square (two degrees of freedom, p-value = 0.05).

4.5 Audience potentially considered by students

Answers from Question 16 (see Fig. 1) led to the results depicted in Fig. 6. Most evident differences have been observed for the "suppliers" and "teacher" stakeholders. In particular, industrial design students perceived the need to interact with suppliers, with a sensibly higher percentage if compared with engineers (38.3% vs 12%). Also for the teacher, the industrial design students (58.6%) highly outnumbered the engineering ones (28%). However, the performed chi-square test (seven degrees of freedom) revealed that considering a standard a p-value of 0.05, the null hypothesis (the differences do not depend on the considered class of students) cannot be rejected.

5 Discussions

5.1 Main evidences and related considerations

The first evidence from this investigation concerns the unexpected difference observed about the background knowledge of additive technologies (Fig. 2). Accordingly, although not validated by the chi-square test, engineering students showed a limited consideration of additive technologies for refining purposes, which is in contrast with the current spreading of the argument for didactical purposes [58]. Furthermore, for the considered design task, industrial design students felt less comfortable in using "only" virtual prototypes (Fig. 3).

Concerning the roles perceived for prototypes, the most unexpected evidence is that engineering students did not consider CAE tools as a support means for communication purposes. It was quite unexpected, since it is acknowledged that even rough and preliminary Finite Element models can provide critical information to be shared with the other stakeholders involved in the conceptual design process. However, this result may depend on the insufficient knowledge that students still had about the design process, at the moment of the survey.

These first evidences imply that the problem can be quite complex, since depending on the specific academic course (and probably also on the specific institution), students have different didactical needs. With the aim of providing a comprehensive set of information about the potentialities of prototypes in design processes, it is evident that didactical programs should be accurately tailored for the specific cases.

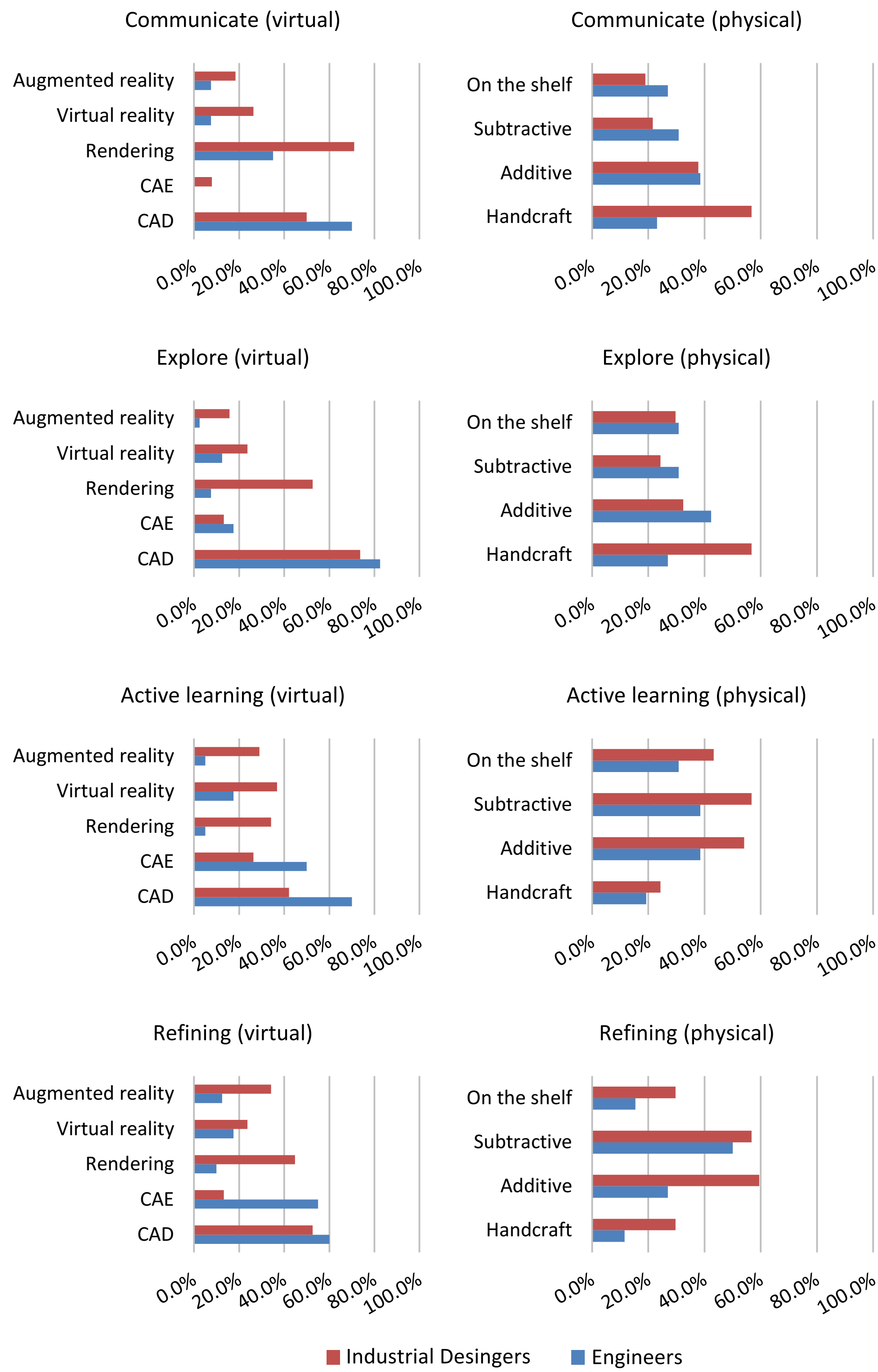


Fig. 4 "Role VS Technology" map of the students' perceptions about the potential usefulness of prototypes for the performed conceptual design task

A further criticality has been highlighted through the results about Fidelity, which show a behavior totally different from what observed by Yu et al. [5]. Indeed, the investigation shows that low-fidelity levels were preferred by engineering students and not by industrial design ones. This conflicting result may depend on several factors, among which: the ambiguous concept of "Fidelity", the particular design task, and the ethnological differences of the courses considered

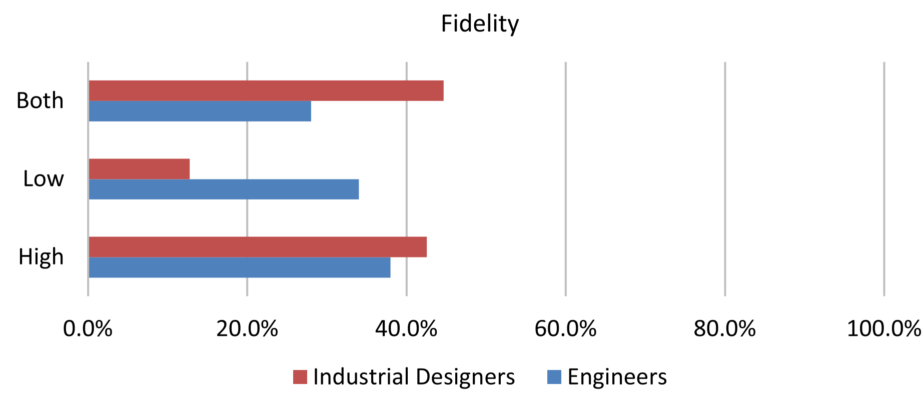


Fig. 5 Fidelity levels considered by students, for prototypes potentially useful for the performed conceptual design task

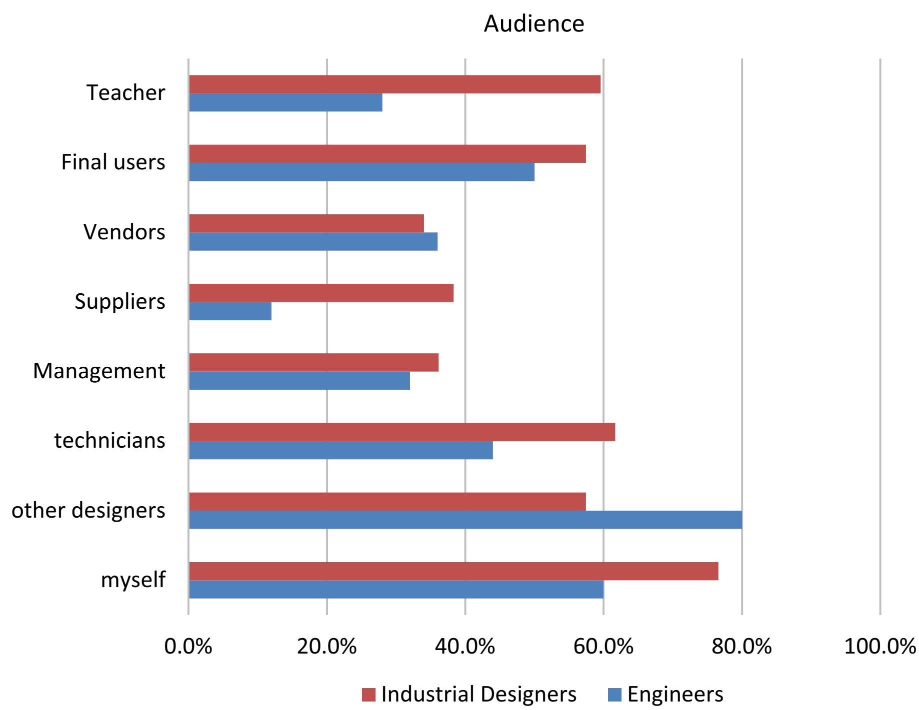


Fig. 6 Audience at which students would be referred with their hypothetical prototypes

in the mentioned literature contribution. Nevertheless, this result confirms (for the considered institution) the need of tailored didactical programs with more emphasis on the interrelated implications within prototyping and design activities.

Eventually, concerning the considered audience, while the difference observed for the "supplier" stakeholder can be explained with the minor technological background of the industrial design students (and then with a higher need to elicit information from suppliers), what observed for the "teacher" cannot be explained in a trivial way. However, it somehow demonstrates that the two courses are characterized by teaching approaches with different teacher-student interactions.

5.2 Expected impact

The impact from this work is twofold. First, there is an impact for the considered institution, since the observed results implies that there is the need to improve the related Engineering and Industrial Design courses, with more comprehensive information about how to exploit the potentialities of the different prototypes in early conceptual design activities. More in general, this work paves the way for more comprehensive investigations aimed at better understanding the highlighted problem, which could extend also to the subsequent phases of the design process. As mentioned above, from the preliminary results depicted in Fig. 3, there subsists a consistently different students' perception about the typologies of prototypes that could be used for the performed conceptual design task. Oversimplifying the results, it seems that engineering students struggle with all freedom offered by physical prototyping, especially AM-based one, because the majority of their coursework focuses on problem solving, design specifications, meeting requirements, and avoiding failures (even in the conceptual phase). Meanwhile, industrial designers are less educated to use virtual prototypes and simulation (especially FE) to preliminarily test their design and therefore are more ready to take into considerations the ambiguity and uncertainty of their conceptual design thus challenging the assumptions and constraints for any problem they face.

These two different perceptions of prototypes use in conceptual design can be somehow brought closer together; by enhancing an interactive teaching process leveraging the design freedoms of additive manufacturing in a more opportunistic way [59] it could be possible to teach engineering students to look for new shapes or new concepts with a creative approach based on the premise that there is no limit on feasible shapes and on materials distribution using AM. At the same time, an interactive approach could provide industrial designers with more insight on the mechanical constraints which will be faced in the following design phases and which could lead to non-negligible changes on the designed product. Such an innovative interactive approach will require innovative tools to turn design concepts into digital, analytic, and manufacturing models. Therefore, interactive aided design tools such as CAD modelling system, CAM simulation and inspection system, CAE simulation systems are deemed essential to deal with design requirements, geometric and topological constraints and physical behavior of the conceptual product [60].

Secondly, this paper provides an investigation procedure that can be reused for repeating similar investigations in other didactical and/or ethnological contexts. In particular, the simple and agile approach proposed here, allows to rapidly perform investigations within single courses, by exploiting common in-class design exercises. Accordingly, the proposed research method and the achieved results, although limited to a single university, pave the way for more extended investigations aimed at better understanding the needs of students when dealing with prototypes in design processes.

5.3 Limits and future developments

Several limits can be ascribed to this work, but the most impacting one concerns the availability of data from courses belonging to a single university. Unfortunately, the absence of further data doesn't allow to obtain generally valid information.

Another limit concerns the lack of more detailed data about the reasons behind the answers provided by students. Therefore, additional interviews should be used to better investigate the actual understanding that students have about prototypes and prototyping activities. Accordingly, repeating the experiment with additional classes and programming additional interviews during the course (similarly to Böhmer et al. [49]), constitute possible future developments of this work.

Protocol analysis of design processes performed by students where prototypes are actually built and used, are certainly a more comprehensive approaches. Moreover, the limited time allotted for the design task, as well as the concise description of the problem to be solved could have hindered the identification of additional details.

Also the consideration of a single design task is a non-negligible limitation of this study. Indeed, different design task potentially lead to different prototyping needs, which could highlight different behaviors from the two groups of students. Moreover, the engineering nature of the considered task may have hindered a more comprehensive understanding of the actual needs of Industrial Design students.

Therefore, it is worth to highlight that the adopted investigation approach should be used only for preliminary investigations, aimed at identifying most critical flaws on the current courses.

Future studies aimed at extracting generally valid ethnological information should therefore consider the following points:

- Investigations extended to different institutions from different countries, in order to extract generally valid information
- Consideration of more realistic design tasks, for example exploiting capstone projects.
- Interviews to be performed to the survey respondents, in order to gather comprehensive information about their actual understanding of the considered definitions, as well as the motivations behind their answers

6 Conclusions

The work described in this paper aimed at performing a first investigation about how students actually perceive the usefulness of prototypes in early design phases. This kind of investigation is crucial for understanding the reasons about the difficulties observed in literature, concerning the development of successful prototyping strategies in design processes. Indeed, while prototyping techniques and technologies are successfully taught in many institutions (as for the considered university), very often there is a lack of integrated courses showing "how" to exploit prototypes in early design phases.

To reach the target, a survey has been performed on students from both Engineering and Industrial Design from the same institution, after the fulfillment of a specific conceptual design task. More precisely, after the completion of the design task, students attended to a short presentation about the different types of prototyping technologies. After that, they participated at the structured survey.

Several limits characterize this work, and in particular, it is not possible to extract generally valid considerations. Nevertheless, the extracted information highlights the need for a "re-design" of the considered courses of the University of Florence, in order to allow students to better exploit the potentialities of prototypes. However, the problem appears to be quite complex, and there is the need of additional data to comprehensively develop successful academic programs. Some important hints have been provided in this paper, about how to perform more extended studies. Accordingly, besides the need of additional information for local purposes, this paper highlights that results from different ethnological backgrounds can be very different or even conflicting each other. Indeed, recent studies found that Industrial Design students prefer low-fidelity prototypes, while engineers often use high-fidelity ones. Differently, this work highlight the contrary, thus confirming the fuzziness of the currently available information about the actual roles of prototypes in design processes.

There is still a lot to do in order to understand the potentialities of prototypes, which however are of fundamental importance for industrial success, and then need to be comprehensively investigated.

Funding Open access funding provided by Università degli Studi di Firenze within the CRUI-CARE Agreement.

Appendix

See Fig. 7.

Fig. 7 Examples of professional ladders provided in the design task description

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