IDENTIFYING PROTOTYPING COMPETENCIES AND ROLES IN EDUCATION

Vanessa Y Y CHIA[1], Franklin ANARIBA[1], Carlye LAUFF[2] and Lucienne T M BLESSING[1]
[1]Singapore University of Technology and Design, Singapore
[2]University of Minnesota, United States of America

ABSTRACT
There have been recent efforts at the Singapore University of Technology and Design (SUTD) in identifying levels of design competency to support teaching and assessment, which has resulted in the development of the Design Competency Assessment (DesCA) framework. One competency area in this framework is prototyping. To understand the nature of prototyping activities, an extensive literature review was conducted along with an empirical study at SUTD to address the following research questions: *How do individual instructors define prototyping? What roles do prototypes play in the design process in courses at the university? What prototyping frameworks, methods, and tools are introduced in these courses?* Herein we report preliminary results based on 17 interviews with SUTD instructors from different disciplines, who teach, supervise, or are interested in prototyping. Insights from this work include: (1) variations in definitions of what a prototype is across different fields, (2) lack of intentionality in prototyping, and (3) missing associated competencies, including how to select appropriate prototyping methods and tools. Taken together, these insights will allow us to re-examine the way prototyping is taught and how prototyping is represented in the DesCA framework.

Keywords: Role of prototypes, prototyping strategy, competencies, design education, design thinking

1 INTRODUCTION
Prototyping is a key feature of design and a common activity in design education. We define a prototype to be "a physical or digital embodiment of critical elements of the intended design, and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process" [1]. Literature has established the importance of prototyping in design education. Prototyping with a clear purpose allows students to avoid wasting costly resources while maximising the opportunity to obtain valuable insights for improvement [2][3]. Yet, prototyping is "consistently described as a one step process" when taught [3], with the focus on the building of prototypes themselves rather than the whole process, including planning, analysing results from testing and communicating. The authors have been involved in design education for many years and can confirm this first-hand: prototyping is often seen as making without much thought into what, why and how. Our literature review reveals that, apart from competencies required to build prototypes, those required for comprehensive and successful prototyping are not always clearly defined. This may be the reason that these competencies are often not explicitly taught nor assessed. While design literature does provide a wide range of design support for prototyping, i.e., frameworks, methods, and tools [4][5], these are not often incorporated into education or linked to specific prototyping competencies. Our research aims to identify the role of prototyping in education, how it is taught and assessed, what competencies are required, and—in subsequent work—integrate this understanding and suitable methods and tools into a design competency framework to support educators.

1.1 State of the art and research questions
Purposeful prototyping is linked to an understanding of the different roles that prototypes play in design [6]. These roles have been summarised at various levels of detail in ref. [1][7][8]. While students who have taken undergraduate engineering design courses might be familiar with the classification of prototypes along the physical/analytical and comprehensive/focused dimensions [9], they might be unaware of the existence of other prototyping frameworks [8][10][11][12]. In addition, heuristics have been used to describe prototyping strategies in design science [2][3], yet these are not often applied in

design education. Most salient of all tools have been developed, such as the prototyping canvas [13] and the prototyping planner [14], which show promising results, but have yet to be disseminated and integrated with design support currently being used in design education [5].

While some work has compiled and related design support to various phases of the design process [15][16][17], most support, including that for prototyping, does not make explicit the design competencies they foster or require. We follow in our research the prior work on competencies at our university, the Singapore University of Technology and Design (SUTD), defining competency as an overarching term comprising knowledge, skills, attitudes and behaviours [18]. Knowing these competencies will help in the design of courses and programmes.

This prior work includes the Design Competency Assessment (DesCA) framework which maps design competencies to phases in the design process, learning outcomes, and associated design support, to enable instructors to plan and develop the design content of their courses in a manner that facilitates teaching and assessment [19]. DesCA is still a work-in-progress. The research reported here adds value by exploring the nature of prototyping activities carried out at the university to provide preliminary insights to the following research questions:

RQ1: How do individual instructors define prototyping?

RQ2: What roles do prototypes play in the design process in courses at the university?

RQ3: What prototyping frameworks, methods, and tools are introduced in these courses?

This will provide the basis for defining prototyping competencies.

2 METHODOLOGIES

2.1 Participants

The study methodology involved in-depth interviews conducted between June and September 2021 with instructors of undergraduate courses at SUTD that involved prototyping. We approached the course leads of all courses, that, according to the course descriptions available from the different pillar/cluster websites, were requiring a prototype as one of the deliverables, using a preliminary definition of a prototype—anything that is a physical or digital artifact. In total, 79 email invites spanning 68 courses were sent out, with 17 course leads agreeing to participate in the study. Course leads who were also instructors of other shortlisted courses were interviewed about each course they taught, resulting in data of 27 courses, representing each of SUTD’s pillars and clusters (Table 1).

Table 1. Participant breakdown by affiliation

Affiliation	Pillar/Cluster	Contacted	Responded
Architecture and Sustainable Design (ASD)	Pillar	14	2
Engineering Product Development (EPD)	Pillar	21	2
Engineering Systems and Design (ESD)	Pillar	13	2
Humanities, Arts and Social Science (HASS)	Cluster	3	2
Information Systems Technology and Design (ISTD)	Pillar	19	4
Science, Mathematics and Technology (SMT)	Cluster	9	5
	Total	79	17

2.2 Data collection

Instructors were given a choice between online or in-person interviews. Prior to the interview, instructors were briefed about the study, asked for permission for an audio recording to be made, and asked to share course materials. Two instructors declined audio recording. In those cases, handwritten notes were taken by the interviewer instead. All interviews were conducted solely by the student researcher (first author), with the co-investigator (second author) observing two of them. Interview questions spanned (1) the instructor’s perception of prototyping, (2) the purpose and nature of prototypes done in the course/project, (3) prototyping skills students can expect to learn by the end of the course/project, (4) prototyping tools and methods taught/used in the course/project, and (5) the assessment of prototypes and prototyping competencies. Questions that were not applicable to an instructor, based on their descriptions of what was done in a course/project, were skipped over at the interviewer’s discretion. Each interview lasted about an hour.

2.3 Data analysis

Transcription of audio recordings were performed using Microsoft Word's *Transcribe* function. Initial coding was done in Microsoft Excel in the following ways for each research question.

To answer *RQ1: How do individual instructors define prototyping?*, examples of prototypes and non-prototypes provided by instructors were classified, with their reasons as to what differentiates a prototype from a non-prototype noted. Future work will use inductive coding on the responses.

To answer *RQ2: What roles do prototypes play in the design process in courses at the university?*, abductive thematic analysis was first carried out on instructors' responses to relevant questions asked. Coding was subsequently expanded to the entire interview when it was noticed that answers to other questions asked contained implicit purposes of prototyping. An abductive approach provided a foundation for prior literature on the roles of prototypes to be incorporated, while allowing new themes from our study to emerge. In particular, the seminal work by ref. [1] on the role of prototypes in companies was chosen for a priori codebook development over the comprehensive literature review in ref. [8] because the former provided a more fine-grained set of categories of roles than the latter. However, the empirical study conducted by ref. [1] differed from our study as the former took place in an industrial context, whereas our study is based in an educational context.

To address *RQ3: What prototyping frameworks, methods and tools are introduced in these courses?*, a more exploratory analysis strategy was taken, whereby any frameworks, methods, and tools mentioned were listed and grouped into categories.

3 RESULTS AND DISCUSSION

The results presented below are preliminary and only cover the first three research questions of our project. A comprehensive and in-depth analysis of the interviews is still ongoing at the time of writing.

3.1 Variations in definitions of prototypes

While most instructors could agree that prototypes are works-in-progress, we observed wide-ranging definitions, with variations across pillars/cluster. Examples cited by instructors from the ISTD pillar include software, programmes, and applications, while ESD pillar instructors felt that only algorithms or software with a certain degree of functionality can be considered prototypes. Instructors from the EPD pillar tended to regard prototypes as physical objects with certain functions, while ASD pillar instructors referred to scaled physical models and virtual artifacts as prototypes. An interesting observation was the translation of prototyping into instructors' own disciplines, best exemplified through instructor SM02 (mathematics).

SM02: If you think of a prototype being a model, like a mathematical model of how you find the velocity of an object given some acceleration data, at the end what you produce is a model that approximates the acceleration somehow. You could think of that as a 'soft' prototype.

We also noticed that only a few instructors were aware that variations exist in the perception of what a prototype is, but this was not articulated unless prompted. This could mean that instructors might not be actively aware of the possibility that definitions of prototypes can vary between disciplines, and therefore, might not communicate this to students.

3.2 Contention along the boundaries of what makes a prototype

In addition, we found certain areas of contention between what instructors would and would not consider prototypes, such as sketches, drawings, diagrams, and numerical simulations. Apart from being field dependent, we posit that these discrepancies might also be linked to purposes of prototyping perceived by instructors. For example, if the purpose of prototyping is to facilitate communication between designers and end-users, then every sketch, drawing and diagram should be considered a prototype. However, if the purpose of prototyping is solely to aid in learning about the technical feasibility of a functional subsystem, then the abovementioned might not be considered as prototypes. This level of metacognition was not articulated by any of the instructors, and we hypothesise that it is likely not communicated to students either. The implication of the above observations is that as students proceed from a common first-year curriculum into their respective pillars (majors), their perceptions of prototyping might become pillar dependent. However, when students work together in multidisciplinary teams for their mandatory final year capstone design project, these variations in definition might create misunderstanding and miscommunication in the team.

3.3 Lack of intentionality in prototyping

We found that purposes of prototyping varied across pillars and clusters as well (Table 2). While we did not ask instructors if these purposes of prototyping were communicated to students, in our experience they are not. Hence, students might fail to appreciate the roles and importance of prototyping in the design process. Moreover, we discovered in courses that have a stronger industry focus, such as in ESD, the roles of prototypes are similar to those found in industry [1], whereas in EPD, there seems to be a gap between the views of industry and education on the purposes of prototyping, despite design projects done in collaboration with industry, such as the capstone design project. We also note that some instructors did not really explain why they chose to include prototyping in their courses, such as in the case of instructor IS03 (software).

Interviewer: Based on your own definition of prototyping, would you say a prototype is necessary for each of these courses you teach?

IS03: So, the short answer is definitely, yes… I mean, I cannot imagine a software engineering course which does not have [prototyping]. It would be quite necessary. I don't know how I can elaborate.

Interviewer: So, my next question is, why do you include prototyping in your course? I understand that based on what you said for the software engineering side…

IS03: I mean, this is just the nature of the course. You know, like you are teaching a software development course from a problem statement to the prototype, but without effort or time like it's a direct contradiction, right?

This reflects a possible lack of intentionality for prototyping, which exacerbates the problem of incongruity within activities carried out in those and subsequent courses. Students cannot be expected to understand the purpose(s) of prototyping if these are not communicated to them.

Table 2. Purposes of prototyping in various courses as mentioned by the instructors

Purposes of Prototyping	Common courses*	Pillar/cluster specific courses				
		SMT	ASD	EPD	ESD	ISTD
Gathering feedback for iteration	✓					
Gathering feedback on stakeholder preferences					✓	
Testing of certain functions			✓			✓
Hands-on way of applying concepts taught		✓		✓		
Applying skills taught in the course			✓		✓	✓
Gaining confidence in building artifacts	✓					
Encouraging risk-taking behaviour				✓		

* *Design courses that are mandatory for all students*

3.4 Missing competencies during introduction of frameworks, methods and tools

We noticed that no frameworks were mentioned. The prototyping tools and methods that were introduced varied from course to course. When tools and methods are not taught, students are asked to rely on training provided by SUTD's fabrication lab (FabLab) or teach themselves. In the case of most EPD and ASD courses, tools used to prototype, such as laser cutters, 3D printers, and CNC mills and lathes are introduced in the lecture, but students are to rely on FabLab training to learn how to use it. In the case of most ISTD and ESD courses, students learn about tools (e.g., programming languages) and methods (e.g., modular code, object-oriented programming). One competency that was largely missing from the interviews, however, was how to select appropriate (fit-for-purpose) prototyping methods and tools. While some instructors were not cognisant of this competency, those who were gave various reasons for not including this in their courses, ranging from the belief that students should pick up this competency on their own, to a lack of time, such as the case of instructor EP02 (engineering design).

Interviewer: Do you also teach students how to select the best prototyping tool, or is it more like telling them that, 'Oh, I think this is the tool you should use'?

EP02: So, I have one lecture, I think, where I [talk] about the fabrication approaches, when I basically go through in broad strokes, I kind of tackle that. Like so this type of fabrication approaches, for example subtractive [manufacturing], are better for these types of scenarios where you want to achieve this type of resolution or when you're working with these types of materials.

This instructor was one of the very few whose response suggests that a prescriptive approach was outlined to students regarding the selection of appropriate methods and tools albeit in broad strokes. Yet,

it was only upon further clarification that we realised that instructor EP02 was actually aware of the selection strategy. However, we are unsure if this was explicitly taught to students in the course.
EP02: So, for example if you're building a little car, and you need an axle for the drive train. And that axle is meant to support a lot of weight, or a certain weight and have low friction… I would just buy a stock steel or hard metal and cut it to size, or machine something down to the diameter you want. Because with a metal you will get a higher load capability, and also when you machine it with a lathe, for example, you can get a smooth surface that will give you very low friction. So that's what I mean, that you should keep your objective in mind. What are the functional requirements of the part that you are trying to prototype, and are those aligned with the process that you're choosing?
The implication of not teaching the process of selecting the most suitable prototyping methods and tools is especially salient and threefold: (1) students might waste resources and time by using methods and tools that are not fit for purpose, because they did not consider this, (2) the lessons learnt by students after such trial-and-error processes might contain misconceptions, and (3) students who do not know the fundamental criteria for selection of appropriate methods and tools might find it harder to apply new methods and tools that they pick up in industry. Therefore, there is a need to teach the whole prototyping process based on experiences and expertise in the respective fields to enhance student learning.

4 LIMITATIONS AND CONCLUSION

In summary, based on our sample of 17 instructors, while many agree that prototypes are works-in-progress, variations in what constitutes a prototype exist across disciplines. We found that what individual instructors perceive as the purpose(s) of prototyping in design also influences how they differentiate prototypes from non-prototypes. Unsurprisingly, the roles prototypes play differs between courses. Of the main purposes of prototyping [1]—enable communication, aid in learning, and inform decision making—enabling communicating was not mentioned by our interviewees. We did find additional purposes, though, compared to the detailed categories of [1] (industry perspective) and [7] (education perspective): hands-on way of applying concepts taught (including chemistry, mathematics, and physics concepts), gaining confidence, and encouraging risk-taking behaviour (see Table 2). We hope this finding triggers a review of the purposes of prototyping in education and a comparison with industry. Furthermore, even though no prototyping framework was articulated by any of the instructors, they do introduce a wide variety of discipline-specific methods and tools, they often rely on FabLab staff to train the students. More importantly, we realised that the competency of selecting appropriate prototyping methods and tools is largely missing in all courses.
The following limitations of the study have been identified. Firstly, the study was conducted at SUTD, whose curriculum arguably has a far larger emphasis on design than most technical universities. The findings may thus be specific to SUTD. Secondly, some instructors provided data about up to three courses, i.e., their view may have influenced our findings more than the views of other instructors. Thirdly, for courses with multiple instructors, as is common in design, methods of instruction can be expected to differ within a single course. Due to time constraints, we have chosen to reach out to course leads, accepting that discrepancies and coherence within courses would be hardly accounted for.
Despite its recognised importance, the purposes and process of prototyping seem to lack explicit attention in education, where large differences in understanding about the role of prototyping exist. It is necessary to identify the competencies, methods and tools required for effective prototyping, accounting for differences between disciplines, and to develop a framework to aid instructors and students. This will be the focus of our future work, which centres on DesCA [19] as the integrating framework.

ACKNOWLEDGEMENTS

Financial support from the SUTD Undergraduate Research and Honours Programme (SGPRSSHARP) is acknowledged. The authors thank EPD undergraduate Anshiqa Agrawal for help in transcribing.

REFERENCES

[1] Lauff C.A., Kotys-Schwartz D. and Rentschler M. E. What is a Prototype? What are the Roles of Prototypes in Companies?. *Journal of Mechanical Design*, 2018, 140(6), p.061102.
[2] Camburn B., Dunlap B., Gurjar T., Hamon C., Green M., Jensen D., Crawford R., Otto K. and Wood K. A Systematic Method for Design Prototyping. *Journal of Mechanical Design*, 2015, 137(8), p.081102.
[3] Christie E. J., Jensen D.D., Buckley R. T., Menefee D. A., Ziegler K. K., Wood K. L. and

Crawford R. H. Prototyping Strategies: Literature Review and Identification of Critical Variables. In *2012 ASEE Annual Conference & Exposition*, Texas, USA, June 2012, p.25.1091 (American Society for Engineering Education).
[4] Blessing L. T. M. and Chakrabarti A. *DRM: A Design Research Methodology*, 2009 (Springer, London).
[5] Hansen C. A. and Özkil A. G. How We (Sometimes Do Not) Evaluate Design Support: A Review of How Design Support Is Evaluated in Practice. In *Proceedings of NordDesign 2020*, Lyngby, Denmark, August 2020, pp.1-12 (The Design Society).
[6] Petrakis K., Wodehouse A. and Hird A. Physical Prototyping Rationale in Design Student Projects: An Analysis Based on the Concept of Purposeful Prototyping. *Design Science*, 2021, 7, p.e7.
[7] Petrakis K., Hird A. and Wodehouse A. The Concept of Purposeful Prototyping: Towards a New Kind of Taxonomic Classification. In *Proceedings of the Design Society: International Conference on Engineering Design*, Vol. 1, No. 1, Delft, The Netherlands, July 2019, pp.1643-1652 (Cambridge University Press).
[8] Menold J., Jablokow K. and Simpson T. Prototype for X (PFX): A Holistic Framework for Structuring Prototyping Methods to Support Engineering Design. *Design Studies*, 2017, 50, pp.70-112.
[9] Ulrich K. T. Eppinger, S.D. *Product Design and Development, 6th Edition*, 2016 (McGraw-Hill Education, New York).
[10] Thomke S. H. Managing Experimentation in the Design of New Products. *Management Science*, 1998, 44(6), pp.743-762.
[11] Moe R. E., Jensen D. D. and Wood K. L. Prototype Partitioning Based on Requirement Flexibility. In *ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Vol. 3a, Utah, USA, January 2004, pp.65-77 (American Society of Mechanical Engineering).
[12] Gill C., Sanders E. and Shim S. Prototypes as Inquiry, Visualization and Communication. In *Proceedings of E&PDE 2011, the 13th International Conference on Engineering and Product Design Education*, London, UK, September 2011, pp.672-277 (The Design Society).
[13] Lauff C., Menold J. and Wood K. L. Prototyping Canvas: Design Tool for Planning Purposeful Prototypes. In *Proceedings of the Design Society: International Conference on Engineering Design*, Vol. 1, No. 1, Delft, The Netherlands, July 2019, pp.1563-1572 (Cambridge University Press).
[14] Hansen C. A., Jensen L. S., Özkil A. G. and Pacheco N. M. Fostering Prototyping Mindsets in Novice Designers with the Prototyping Planner. In *Proceedings of the Design Society: DESIGN Conference*, Vol. 1, Cavtat, Croatia, May 2020, pp.1725-1734 (Cambridge University Press).
[15] Sanders E. B. N., Brandt E. and Binder T. 2010, November. A Framework for Organizing the Tools and Techniques of Participatory Design. In *Proceedings of the 11th Biennial Participatory Design Conference*, Sydney, Australia, November 2010, pp.195-198 (Association for Computing Machinery).
[16] Castaños C., Chin A., Jiang J., Kim E., Kramer J., Nitta C., Ryu S., Shkurti J., Agogino A., Beckman S., Poreh D., Roschuni C. and Yang M. *The Design Exchange – BEST Lab at UC Berkeley*. Available: https://best.berkeley.edu/best-research/thedesignexchange [Accessed on 2022, 9 March].
[17] Lauff C., Wee Y. H., Teo K., Png S., Swee A., Collopy A., Vargas B. and Wood K. L. *Design Innovation Methodology Handbook: Embedding Design in Organisations*, 2021 (Singapore University of Technology and Design-Massachusetts Institute of Technology International Design Centre).
[18] Thandlam Sudhindra S., He Y. J., Blessing L. T. M. and Khan S. A. Stories of Design Education: An Analysis of Practices and Competencies. In *Proceedings of the Design Society: DESIGN Conference*, Vol. 1, online, May 2022 (Cambridge University Press).
[19] Thandlam Sudhindra S. and Blessing L. T. M. A Framework for Design Competency Assessment. In *Proceedings of the Design Society: ICED21*, Vol. 1, Gothenburg, Sweden, August 2021, pp.91-100 (Cambridge University Press).