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Creating new 3D forms in collaborative product design

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Abstract
In collaborative design settings, designers communicate and explicate their ideas visually and verbally in order to reach a shared understanding. The verbal exchanges of group members engaged in a joint design task provide rich data regarding the design activities being undertaken by the group members. In addition, sketching and modelling are recognized as essential for designers to examine and produce design ideas at the very beginning of a re-design process. This exploratory case study focuses on collaborative design activities and problem–solution co-evolution among the various design disciplines that students engage in during their product design processes. Nine students from three design disciplines (interior design, product design, and graphic design) participated in a workshop providing knowledge about 3D modelling, following which they undertook a re-design task to develop a new 3D form of a detergent bottle. The research data consisted of video recordings and sketches, and the analysis focused on the progress of the design processes and the differences between the groups. The results highlight that the creation of new 3D forms was based on intensive reformulation activities such as setting new problem expressions or modifying existing ones. This kind of re-design task, which presented constraints in terms of developing a new 3D form within the prescribed requirements, served as a good exercise through which to practice co-evolution because it drove the design activities towards a balance of transitions in the problem and solution spaces.

Keywords
co-evolution; collaborative design; problem-solving; product design; sketching; 3D model

Introduction
The main purpose of teaching art and design is to enable students to learn domain-general and domain-specific knowledge as well as apply practical skills related to the art and design field, through which students' enthusiasm, participation, and professional skill can be extended. All design students perform some type of design activity, such as improving a production process, developing functions, planning a project, or creating new forms. Current design education highlights that sketching and digital as well as manual model-making are essential creative design skills. Graduating designers must have a solid understanding of the design process and should be able to apply these skills in a variety of situations.

In the last few decades, as digital design applications have emerged and been absorbed into design practice, they have been recognized as a technology of enormous potential for design (Wu et al., 2012; Ye et al., 2008). Therefore, 3D modelling and rapid prototyping skills have become essential techniques in design education. Various modelling techniques, such as the application of curved surface modelling software (e.g., SolidWorks), direct the vision of design as continuous and integrated processes of ideation and construction. Thus, from the very beginning of a product's appearance development, designing is focused on creating and developing design ideas that are given an initial 3D form. Designers make sketches not just to record an idea but also to help generate it, and sketches are central to the emergence of new thoughts (Menezes & Lawson, 2006). Therefore, ideation involving the visualization of design ideas plays a crucial role and represents a critical aspect of collaborative designing: Proposed and externalized design ideas might provide external stimuli for the emergence of new ideas within a team, which can become objects of shared discussion and evaluation. Nik Ahmad Ariff et al. (2012) described this cognitive process during sketching as an exploration, interpretation, and re-interpretation cycle.

Design researchers have found that problems and solutions co-evolve during the design process (Dorst, 2019; Dorst & Cross, 2001; Lotz et al., 2015; Maher & Tang, 2003; Wiltschnig et al., 2013).Thus, it is important to have a deeper understanding of co-evolution in the context of developing design instruction in higher education. The present study focuses on the analysis of the problem–solution co-evolution of student teams as they design a new 3D form of a detergent bottle. The objective of the study is to develop an in-depth understanding of the approaches to designing a novel product form by students from different design disciplines. The objective is divided into the following research questions:

1. How do the teams differ from each other in their design process?
2. How do the collaborating students carry out the design activities under the task requirements?

Background

The co-evolutionary model of the design process

In design research, there are two main frameworks related to design processes: Simon's (1981) rational problem-solving framework and Schön's (1983) reflection-in-action framework. These two frameworks, referred to as the cognitive and situational approaches, respectively, involve fundamentally different ways of approaching the design process (Visser, 2006). The former approach provides insight into process components (cognitive tasks, constraints, operations, and goals), while the latter addresses issues of the design content and situation (Dorst & Dijkhuis, 1995; see also Visser, 2006). Dorst and Dijkhuis (1995) have argued that the problem-solving approach means looking at design as a search process in which the scope of the steps taken toward a solution is limited by the information processing capacity of the acting subject. According to Goel (1995), who championed Simon's (1981) information (cognitive) processing theory, designing is a search in the unitary problem space, and the design process consists of two types of activity: problem structuring and problem-solving. Problem structuring is the phase in which a problem-solver constructs and reconstructs the problem space and design solutions that emerge gradually as a process of structuring, composing, and decomposing the problem (Goel, 1995).

Schön's (1983) design process model is based on naming, framing, moving, and evaluating activities, and the development of a shared framing is acknowledged as an important factor in collaborative design processes (Dorst & Cross, 2001; Zahedi & Heaton, 2017). During the process of framing, designers also create a particular view of the design problem. Based on these activities, the design problem and potential solutions "co-evolve" over time, with the designer exploring the co-existence of two spaces, a "problem space" and a "solution space," and each space informing one another. The co-evolution view of the design process was originally proposed by Mary Lou Maher (Maher & Poon, 1996; Maher & Tang, 2003) and was later applied by Dorst and Cross (2001) to analyze the industrial design process. While these early papers on co-evolution are still widely referenced, there have been few further studies on the framing and co-evolution of problems and solutions within design projects (e.g., Dorst, 2019; Lotz et al., 2015).

Dorst and Cross (2001) analyzed whether their observations aligned with the problem–solution co-evolution model. They observed that framing design ideas iteratively alternates with the problem setting moving toward the proposed solution state. They found that the designers had developed and refined both the formulation of and solutions to the problem through a constant iteration of the analysis, synthesis, and evaluation between the problem and solution spaces in the same manner as Maher's problem–solution co-evolution model (Maher & Tang, 2003). Furthermore, Dorst and Cross (2001; see also Dorst, 2019) conceptualized a clear link with Schön's (1983) problem framing and proposed that creative insight occurs when a problem–solution pairing is framed. They indicated that this problem–solution framing ability was crucial in creative design disciplines. Within this co-evolution view of design, potential design solutions receive consideration in the context of the requirements defining the problem, and design requirements can be adapted in light of novel solution attempts. In this sense, the design process is the parallel evolution of both the problem and solution space dimensions. Further, Lonchampt et al. (2004) analyzed how the problem and solution spaces co-evolve during collaborative design and how two states can be considered to be shared within the design group. They considered design activity as an elementary process that allows shifting from one situation to another, either the solution definition or the problem expression, and how the shared knowledge about them changed. To improve the evolution between the problem and solution spaces through a focus on and appropriation of activities, it is important to understand that the shifts between these spaces are associated with alternative proposals and the emergence of new criteria (Brissaud et al., 2003). According to Dorst (2019), there is a need for further research, especially in terms of the transitions that represent jumps from the solution space to a new problem definition.

Wiltschnig et al. (2013) examined the validity of a problem–solution co-evolution model of design behavior. Their data consisted of audio and video recordings of meetings held by a five-member design group who worked around various product development stages over five months. They analyzed whether the design episodes were collaborative or individual. Collaborative episodes mean that one member mentions the requirement and other team members propose solutions. Individual episodes mean that both the change in requirements and solutions are proposed by the same individual. They found that the problem–solution co-evolution was most often collaborative in nature. The collaborative episodes involved a variety of directional movements between the problem and solution spaces, and co-evolution activity was dominated by requirements analyses leading to solution attempts. However, they also found numerous instances through which solution attempts sparked requirements analyses, which often resulted in requirement changes.

Sketch-based ideation in teams

In professional design, the importance of sketching and producing various representations has been highlighted (Ferguson, 1992; Goel, 1995; Nik Ahmad Ariff et al., 2012). In collaborative design settings, designers communicate and explicate their ideas visually and verbally in order to reach a shared understanding. Sketching and modelling are recognized as essential in enabling designers to examine and produce design ideas at the very beginning of the design process (e.g., Suwa & Tversky, 1997). Designers examine their designs in several overlapping ways, including through diverse types of sketches, notes, and models of various sorts, and these representations play important roles in different phases of the design process (Ferguson, 1992; Goel, 1995). The skilled use of external representation provides opportunities to define the salient attributes of the design problem and, at the same time, evaluate the appropriateness of the developing solution (Pei et al., 2011).

Professional designers sketch for a reason—the most obvious being to show how a design will look and function (Ferguson, 1992) without the need to construct the actual object. Sketching is an acknowledged thinking tool for designing, but it is also a tool to evaluate and test ideas (Goel, 1995; Schön, 1983). The explorative cycles of sketching, reinterpretation, and evaluation are central to the production of design ideas (Menezes & Lawson, 2006; Nik Ahmad Ariff et al., 2012). Furthermore, Ferguson (1992) distinguished the thinking sketch, the talking sketch, and the prescriptive sketch. Lotz and Sharp (2017) explained that the talking sketch was common in collaborative design because constructive interaction required designers to talk to each other. In their classification, the talking sketch means simultaneous sketching and talking so that either one participant is sketching on behalf of the team or co-sketching where co-designers sketch while talking.

Further, Goel (1995; see also Seitamaa-Hakkarainen & Hakkarainen, 2000) observed two contrasting sketch development strategies. The first, labelled horizontal sketch development, is described as a move from one design idea to another more-or-less different idea. The second, labelled vertical sketch development, is to move from a design idea to a more articulated and detailed version of the same idea. Horizontal sketch development indicates that the designer goes over several design ideas without articulating any of them in depth. This means that the resulting sketches are not clearly connected to each other and that the degree of detail or complexity of these sketches do not increase (see Goel, 1995). Vertical sketch development means that the drawings are closely connected to each other; the sketches being developed become increasingly more detailed and complex and consist of an increasing number of design elements. In what follows, we describe our research setting, participants, method of data collection, and data analysis.

Method

Participants and context of the study

The aim of the study was to analyze how students from three design disciplines would approach the design of a novel product form. We focused on how collaborating students carried out a well-structured design task and how the co-evolution of the design activities occurred. For our exploratory case study, a workshop titled Rapid Modelling Techniques was organized in the summer of 2020 at an art and design college. This was an optional course offered to third-year undergraduate students of the three design disciplines: graphic design, interior design, and product design. It consisted of 21 hours of workshop training over seven weeks, lectures about computer aid design, and acquiring relevant knowledge about design thinking in product design context. Twenty-six third-year design students attended the workshop, which provided them with basic skills in the use of the SolidWorks software. The end part of the workshop was the focus of the data collection for the present study.

The product design students had used SolidWorks earlier, and the interior design students had some previous experience using the other 3D modelling software (3D Max). However, prior to the workshop, the graphic design students had no experience of using 3D software. The goal of the workshop was to fulfil the requirements that all participating students would have some experience of rapid prototyping in order to collaborate during a product design task. Based on this assumption, we were interested in the potential differences between the three design teams as they underwent the same product re-design task.

In this study, we focused on the nine students who volunteered to participate in the experiment. They were assigned to one of three groups based on their design discipline and were asked to undertake a product re-design task. For simplicity, the three groups will be referred to as G-interior, G-product, and G-graphic in order to highlight their specific design fields. Each team's design process was video-recorded, and the screen recordings were used during the rapid prototyping stage. We also collected their resulting sketches, digital models, and design artefacts. The present study concentrates on the problem–solution co-evolution process and 2D sketching as a form of creating. A detailed analysis of the 3D modelling and rapid prototyping will be reported in another study.

Design brief

The experimental situation allowed us to focus exclusively on a well-structured re-design problem-solving situation whose aim was to develop a new form of the product using sections on the form as a starting point (see Figure 1). Besides sketch-based ideation, the students were required to use the curved surface modelling software to construct the form of the detergent bottle. The product belonged to a brand called SMOOT, whose market position was mid-range or even higher than that of similar detergent products. The design brief consisted of a problem definition for initiating the re-design and a specification based on the client's requirements. The group members were required to develop, within constrains, the form of the bottle of a detergent product.

The design brief was formulated to cover some predetermined product requirements. The students were asked to follow the requirements below:

- Expand the capacity by 30% based on the original bottle,
- Develop the form by adding novel and desirable features,
- Keep the 3D model similar to the original form by at least 50%,
- Take account of design rationality when dealing with the form and function.

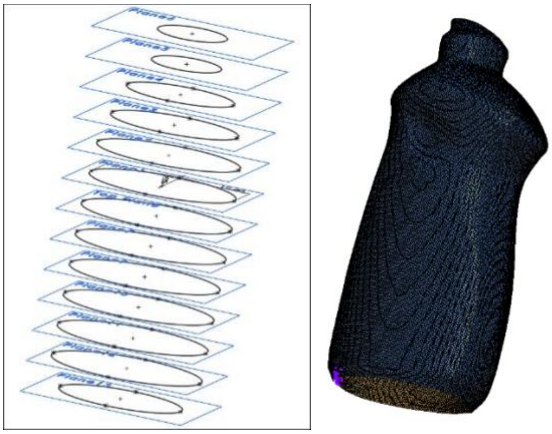


Figure 1. Series of sections adapted to the modelling task and mesh data collected using 3D scanning skills

The duration of the product re-design task was limited to about 2.5 hours, including knowledge seeking, ideation, sketching, and 3D modelling. Each group was required to perform their design activities in succession:

- Defining and framing design problems by talking, writing, and gathering information to explore solutions,
- Ideating by sketching to explore visual features based on the solutions produced,
- Modelling a 3D model with SolidWorks based on the produced 2D sketching.

Data collection and data analysis

The entire design process was video-recorded, and screen recordings were used during the construction of the 3D-models. For the video analysis, we adapted Ash's (2007) approach for tracking design process phases. First, for a macro-level analysis, we segmented the video data into one-minute units and identified the design activities in each unit. Product design activities are generally recognized following the phases of an iterative design process such as problem recognition and analysis, information gathering, idea generation, and evaluation (Goldschmidt & Porter, 2004; Lee & Jin, 2014; Tversky, 2005). Thus, we classified the design activities in the following categories, which were validated in our previous studies (Lahti et al., 2016): 1) analysis constraints, 2) ideation, 3) information seeking, 4) sketching, 5) 3D modelling, and 6) talk about the computer technique. The categories were not mutually exclusive, so the one-minute units could include several activities at the same time, such as ideating and sketching. Based on the categorization, we created flow charts for each group, showing how each design activity proceeded during the session.

In the second stage of the analysis (i.e., micro-level), we focused on the activities of problem–solution co-evolution. This analysis was limited to the time preceding the 3D modelling phase. The focus on the collaborative design process allowed us to observe the problem-solving activity of the participants, especially solution development. Table 1 presents an example of the video recording and transcription of the problem-solving activity. The classification is explained in Table 2. We used the following four categories: 1) proposal, 2) definition, 3) evaluation, and 4) reformulation.

Table 1. Extract from the video-recording in G-interior

Time	Verbalization	Sketching Activities
00:03:28	Z: Um, you should add a little decoration on it. D: Look, there is also (a need) at the bottom.	 Normal camera view from the top angle.  Stylized camera view from tripod camera.

Table 2. Categories and excerpts of the co-evolutionary design statements

Proposal (PD)	Proposing and explaining a new solution (or new elements of a solution).	*...then, is there a little bend? Maybe this half does not need much round...*
Definition (D)	Explaining, interpreting and communicating a proposed solution (or proposed elements of a solution) among design team.	*Right, I think so, um...it is used this shape, then I hope ... There is a bulge we can grasp it using one hand.*
Evaluation (E)	Judging a proposed solution in regard to the problem expressed.	*You give a good idea; I think this can increase the volume of the bottle.*
Reformulation (R)	Setting a new problem expression or modifying the existing one. The first initial problem expression is considered as a particular reformulation.	*...Yeah, have a straight one like that placed in our dormitory.*

Our study relied on descriptive statistics of the encoded data. To compare the differences between the three groups, we compared some of the quantitative differences of the main design activities (time used, frequencies). Since this exploratory study involved three teams, testing the statistical significance of their mean differences would not have been meaningful. First, the time used in the main design activities was represented on a flow chart. Second, for the micro-level analysis, the frequencies of the four co-evolution categories were analyzed. We were interested in the quantity of each category and the variations between the problem-solving activities of the three design teams. We then distinguished not only which activity was more or less involved in the problem-solving phase but also identified how the activities alternated throughout the design process.

Results

A comparison of the design activities

A reading of the brief revealed that the time spent by the groups on the design processes varied between 71 and 111 minutes. The video data were divided into one-minute units related to the various types of activity that we analyzed on the group level. Design activities such as ideation and sketching usually occurred simultaneously, with one participant sketching on behalf of the team while responding to the other team members' suggestions. Also, other members drew sketches in order to improve ideas discussed in the teams. During the early stage of the problem formulation and 2D sketching, the groups worked collaboratively to analyze constraints by proposing, testing, and evaluating design ideas and producing solutions. Next, during the events involving the 3D reconstruction and modelling, the independent work increased, and one member of each group focused on producing the 3D modelling.

Figure 2 presents the timelines of the design activities in each team. G-interior used the least amount of time (71 minutes) to progress through the whole design process and started producing the 3D model after 15 minutes, with G-product doing so after 22 minutes and G-graphic about twenty minutes later (after 40 minutes). Only G-interior had conversations about computer techniques; the SolidWorks program was new to G-interior, and they talked about how to realize the desired effect with certain operations within the software. The discussions about the computer technique indicate that the G-interior team members did not possess the necessary software skills; therefore, they had to discuss how to use certain operations. The timelines in Figure 2 show the design activities during the design sessions. The grey areas at the end of the 3D modelling denote that the video data were changed into ten-minute units.

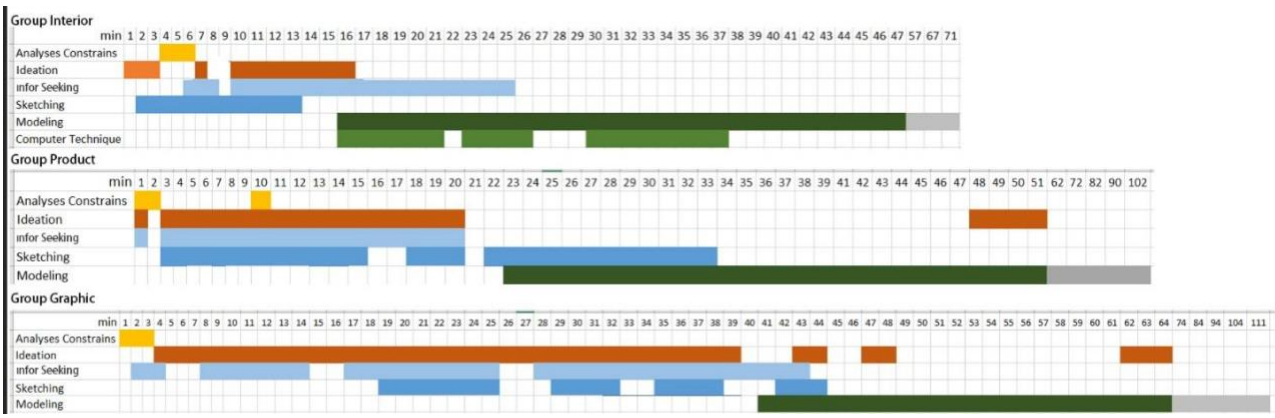


Figure 2. The groups' design activities

The design process began with an analysis of design constraints (G-product and G-graphic), ideating (G-interior, G-product), and information seeking (G-product and G- graphic); however, G-interior and G-product began producing sketches (see Figure 2). The role of information seeking was more like searching sources for inspiration to generate alternatives to sketching. In addition, the information seeking (G-interior) and sketching (G-product and G-graphic) continued even as the teams entered into the process of building the 3D model. Specific to G-interior was that it used up the least amount of time for 3D modelling (56 minutes), ideation (11 minutes), and sketching (12 minutes) compared to the other groups. They quickly developed the idea of a water-related shape and drew various drops form in the bottle sketches (see Figure 3). This corresponds to the idea of vertical sketch development where a proposed design idea is articulated and detailed.

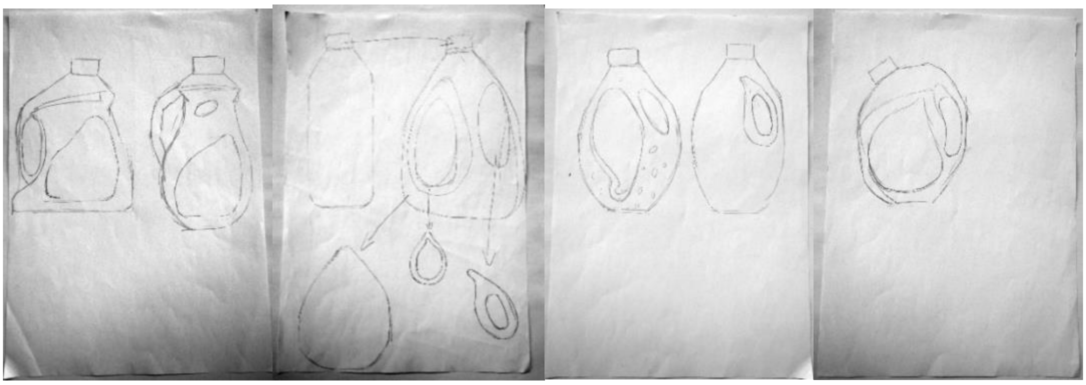


Figure 3. Sketches generated by G-interior

The design process in the G-product team took 102 minutes. Ideation and information seeking proceeded simultaneously (19 minutes), whereas sketching continued into the 3D modelling process. The group members produced a series of 2D sketches, which focused on many details regarding their proposed solutions to the problems or sub-problems (see Figure 4). The sketches were closely connected to each other, developed at increasingly detailed and complex levels, and consisted of an increasing number of design elements (i.e., vertical sketch development). Besides the discussion on creating a detailed form of the bottle, they considered manufacturing-related requirements. One person took responsibility for the sketching while responding to suggestions from others.

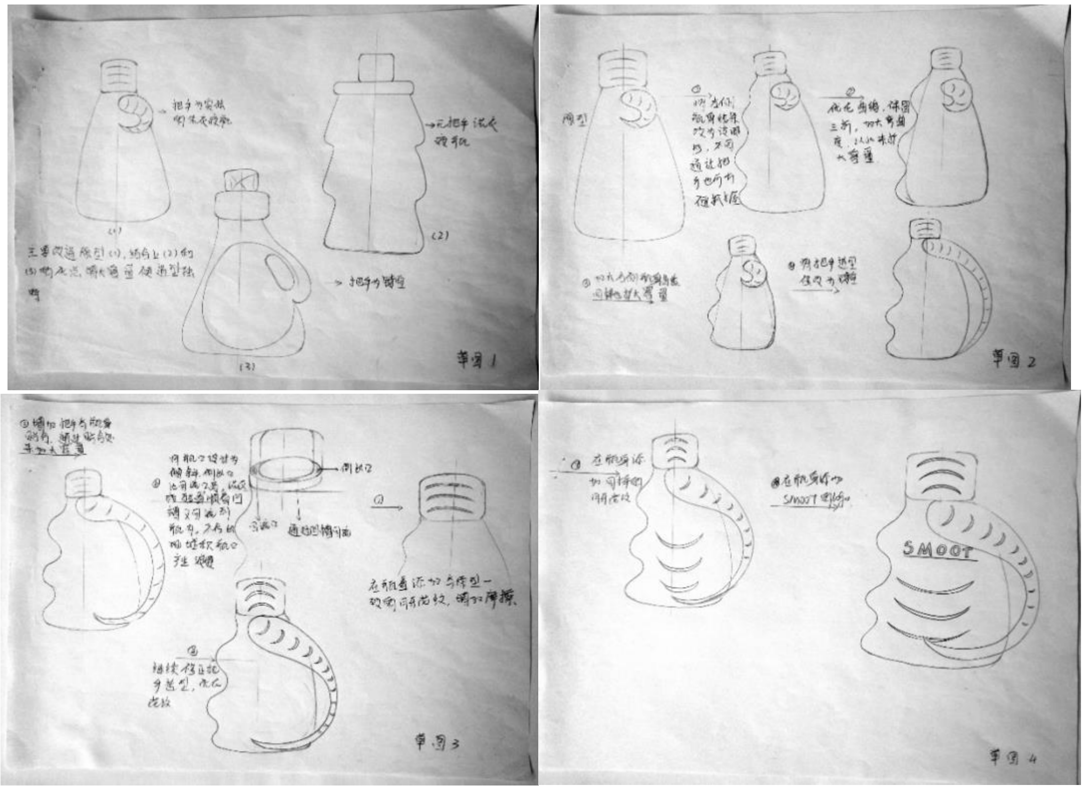


Figure 4. Sketches generated by G-product

In contrast to the other groups, the G-graphic team spent the most time on the design process, with the amount of spent time on the main activities (i.e., ideation and information seeking) doubling that of the G-product team. They also started 2D sketching much later than the other teams. Despite the short period of time spent learning the SolidWorks software, they accomplished a desired 3D model with skills they learned from the workshop. Their sketching process was mainly based on horizontal sketch development because the sketches represented various forms of the bottle that did not increase the complexity of the selected form (see Figure 5).

Figure 5. Sketches generated by G-graphic

A comparison of the problem–solution co-evolution processes

The mixed quantitative and qualitative analyses focused on the co-evolutionary design process of each group. This process involved moving between the problem (design brief and constraints) and solution (proposal of solution attempts) spaces. Accordingly, the co-evolution required a reformulation of the problem state and proposed solutions. As Schön (1983) emphasized, design problems are actively framed or reformulated by designers who act to improve the current situation. Thus, it is presumed that in problem-solving, the reformulation and proposal of a solution are key elements that should be moved into the problem space. Reformulation is setting a new problem or modifying an existing one. Since we were interested in collaborative designing and problem–solution co-evolution while designing a new 3D form, we focused on our detailed analysis in the early stages of the design process, that is, sketching a form of the bottle. As soon as the 3D modelling phase was started, the members of each group turned their working mode from collaborative to individual. It is reasonable to assume that the most competent member in 3D modelling skills undertook the main role during this phase. In what follows, we first provide an overview of each group's problem-solving activities. Second, we deepen the analysis by focusing on how the form developed during the design process and how the groups solved the requirements related to the design brief.

We encoded the verbal problem-solving interactions of the design teams according to the following categories: proposal, definition, evaluation, and reformulation. The time duration of the problem-solving activities and the distribution of the problem-solving statements varied between the design groups: G-product (21 min, $f = 143$), G-interior (15 min, $f = 79$), and G-graphic (40 min, $f = 114$). In other words, G-product was efficient and supplied many problem-solving statements. We calculated the frequency value, which refers to the occurrence of problem-solving activity per minute during the design process. This confirmed the same results: G-product (6.8) had the most intensive problem-solving co-evolution period, followed by G-interior (5.26) and G-graphic (2.85). In addition, we found that the number of statements between the students differed significantly. For example, in G-interior, student A was most active and made most of the statements (45%), whereas student B made 29% and student C 26% of the statements. Student A was most knowledgeable about 3D modelling and the software, so she also knew what forms and aspects needed to be considered. Her statements were important while designing the form for the bottle. Later she also took the main responsibility to make the 3D model with the software.

Figure 6 shows the distribution of four problem-solving categories in each group, the overall distribution of which differed significantly between the teams. The reformulation (R), which involved setting a new problem or modifying the existing one, dominated in all groups. The percentage of the reformulation in G-product was more than half the total (53%) number of problem-solving activities. The corresponding percentage in G-interior was 35% and 39% in G-graphic. However, G-product only recorded a proposal (PD) activity of five percent, which was less than those of G-interior (13%) and G-graphic (15%). These results indicate that reformulation also played an important role in the well-structured re-design task and not only in the ill-defined design tasks. Reformulation drove the teams to explore the problem space more than the solution space.

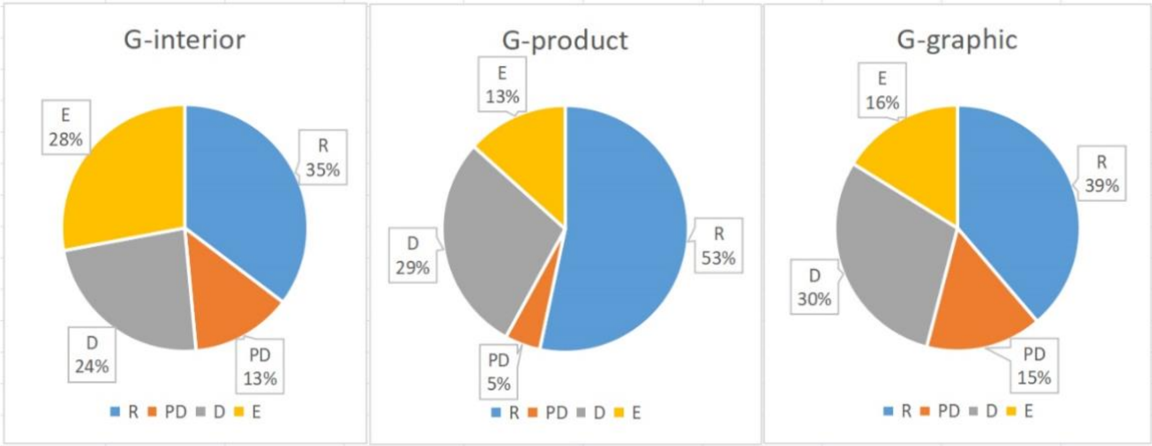


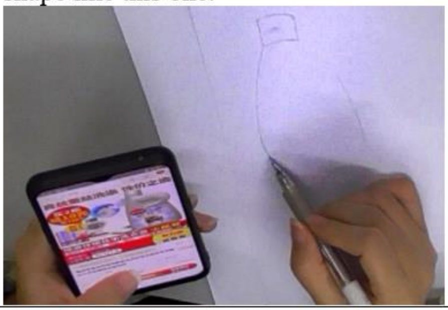
Figure 6. The distribution of problem-solving categories in each group

In the following discussion, we provide a description of each team's co-evolution in developing the 3D form for the detergent bottle and how their solution attempts fit the design requirements provided.

Reformulation as a driver of co-evolution

In relation to the co-evolutionary model of the design process, we found that reformulating the new problem was the driving force in the problem–solution co-evolution process. Table 3 illustrates the transcription of the discussion setting, which comprised the time codes, the students' initials, sketching-related statements, and the categories emerging from the analysis.

Table 3. Extract from a G-product excerpt

Time	Students	Statements	Categories
00:04:18	A	Un, I am thinking if we could change the shape like this one. 	PD
00:04:20	B	Exactly, this is a good idea, yeah.	E
00:04:26	C	Um, I am afraid, do you think a problem this will lead to liquid stacking?	R
00:04:30	B	But we use this shape means to extend the volume, you are right maybe. Um. It was nice I am thinking If we could shape the curve to be flatter and smoother than the original, maybe better.	R
00:04:42	C	You mean decrease the curvature of the curve of shape, then the shape will be changed.	R
00:04:43	B	Correct.	
00:04:50	C	At same time, we need ensure the handle could be hold by a palm when people use.	R
00:04:51	B	um, I think so.	
00:04:55	A	That is to say, lean the curve vertically then the liquid could flow slowly down.	R
00:05:01	B	Yes, no need flatter and smooth too much, but let it much smaller, um.	R

In this episode, G-product focused on a new proposal from student A. Subsequently, an element of the problem was defined by student C, who posed a new problem (*this will lead to liquid stacking*). To solve this, the problem was separately decomposed into two sub-problems (*shaping the curve to be flatter* and *leaning the curve vertically*). However, here, there were no evaluative statements; instead, a putative solution for *shaping the curve to be flatter* was proposed. Following a long discussion, this solution attempt was again shifted toward the problem space with another sub-problem (*leaning the curve vertically*). Similarly, no evaluation ensued; instead, new reformulations were continuously generated by the student team members. It was important that they structured a common ground based on student C's question regarding *liquid stacking*. Subsequently, they continued with the reformulations and set problem expressions to achieve the final form of the bottle. Following a further period of discussion, at 00:11:22, student B first drew a thumbnail sketch to present the resolution of making the bottle flatter and smoother, as shown in Figure 7. During this episode, their activities were fixed on finding solutions to solving the problem of *liquid stacking.* In this sense, G-product focused on reformulating the design problem in functional terms (i.e., specific functions that the form needs to fulfil), which left room for adequate alternative solutions.

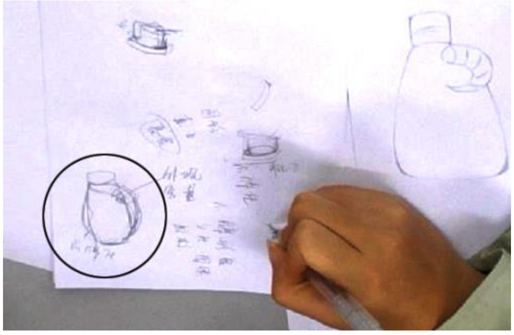
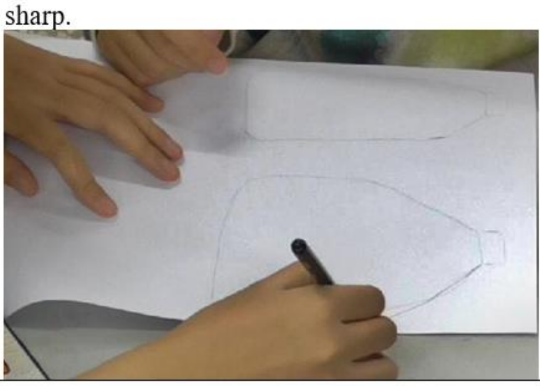


Figure 7. Thumbnail sketch to present the resolution

Creating solutions through definition and evaluation

In G-interior, the key idea of the form of the bottle was the shape of the waterdrop. Table 4 illustrates the transcription for the extracts. The episode shows how G-interior used the shape of the waterdrop to improve the feature of the bottle. In this episode, they did not clearly reformulate the problem statement but relied on definition and evaluation activities.

Table 4. Extract from a G-interior excerpt

Time	Students	Statements	Categories
00:03:50	A	Wait a minute, you should sketch it firstly.	
00:03:53	B	Yes, some rough sketches.	
00:03:58	A	Surely, after we confirm at the end then finally use a fine picture. At here, a waterdrop, it is round and big at the bottom, and top is a little sharp. 	D
00:04:01	C	Look, here also need.	D
00:04:02	A	Then, there is a handle. Hmmm, actually it's needed more changes, we can make it like one entire waterdrop. What do you think?	PD
00:04:09	B	Ahh, take care, that's too big... more than 30%.	E
00:04:12	AC	Ahh…	
00:04:14	A	Um, not too bad, the handle could be at here. And at another side create one more waterdrop feature. But there cannot make it sharp, I cannot make it.	D
00:04:15	B	Um.	
00:04:28	C	Do you want one more hole on there?	D
00:04:29	A	No, no, no.	E
00:04:33	ABC	Ahh…	

Their design episode began with a definition generated by student A about discussing the shape of the waterdrop. Student A simultaneously produced some sketches. The discussion proceeded around the topic of how to use the waterdrop shape for the bottle. Then, student A proposed a description of the shape (*we can make it like one entire waterdrop*), which was rejected by student B. Next, student A defined another element (*create one more waterdrop feature*) for use on the other side of the bottle. Consequently, student C pose the following question: *Do you want one more hole on there?* This question required an evaluation about using the waterdrop shape on the other side, but it was rejected by student A.

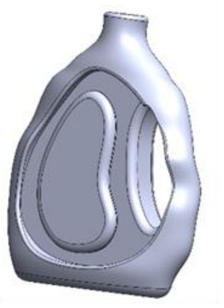
Generating proposals for a satisfactory solution

G-graphic produced more proposals than the other groups. At the same time, they were considering the design constrains from the problem space and did not reformulate the problem state. At the beginning, at 00:00:55, student C proposed adding a handle to the body in response to the requirement regarding expanding the capacity by 30%. They then discussed using the form to solve the problem of expanding capacity. Subsequently, a limitation emerged regarding keeping the model similar to the original form by at least 50%. However, in focusing on the constrains from the problem statements (00:02:37), student C proposed a provisional solution in response: "*Like the original bottle, we only hollow out the body on one side, then we keep on leaving most of the original form*," which garnered support from the members. Relating to adding novel and exquisite features, the members held discussions around suitable novel features for decorating the body of the bottle. At 00:07:45, student C proposed the use of a "*decorative pattern on the body, like that bottle of mineral water*." Therefore, some arguments focused on assessing which patterns were appropriate for such a decoration. Later, at 00:09:05, while considering the constraint of expanding the capacity by 30%, student B proposed another solution to *narrow the underside of the form for similarity with the original form.* Again, at 00:12:04, regarding the decoration idea, student A proposed using a waterdrop shape, and at 00:24:26, student C proposed another alternative that would be "*easy to make its 3D model*." Similar arguments based on aesthetic criteria were proposed in their evaluation and reflection.

Meeting the requirements in the design brief

All groups took responsibility for the product re-design task—they determined the design context and how to proceed with writing, sketching, and modelling. All students attended the workshop to learn the rapid prototyping techniques and later successfully achieved the design solution for the complex design requirements. In the design brief, the students were asked to expand the capacity by 30%, develop a new aesthetic form, and take account of design rationality when dealing with the form and function. Table 5 summarizes the outcomes of the design processes. All final product designs met the requirement of the 30% capacity increase. The students' design thinking involved creative and rational working to evoke design ideas such as the handle of the detergent bottle. However, only the product design students considered the viewpoints of end users during the design process.

Table 5. Summary of the fulfilled requirements

	G-interior	G-product	G-graphic
Expand the capacity by 30%	Through enlarging the size of body to achieve a 30% capacity increase, but they didn't sufficiently consider the aesthetic issues when they designed the bottle.	They sufficiently considered the aesthetics on the shape of the bottle when they formed the shape, then a nice combination was created between the capacity and the aesthetics.	An oval shape was used to create for the bottle's body, also meet the requirement of 30% capacity rise from the design brief.
Develop the form by adding novel features	Adopted the element of waterdrop to create the idea of the bottle's body. The waterdrop shapes were used as three concaves on the surface for creating the body of 3D model.	More novel and detail were considered for 2d sketching and 3D modelling, for some examples, the top cap, the smooth handle, and the logo and curve for decorating.	The body was designed to be of a simple style. They tended to utilize much smooth and bent curve for decoration, such as oval line on the body and used kidney shape creating the handle.
Take account of design rationality when dealing with the form and function	They seemed as using visual elements for their evaluation activity, e.g., *that's too big more than 50% (A), there cannot make it sharp(B).* These statements separately have the meaning on somewhat visual element for their design rational.	Such as the solving problem of *liquid stake up* and *the handle could be hold by a palm* these can be seen as they utilized end user's viewpoints for developing the form.	They always used some similar questions for their evaluation, such as *look at this, it's beautiful, isn't it?* and *Is this beautiful or much complex?* They tended to adopt a judgement confined on 2D visual element for evaluation activities.
The accomplished 3D models			

Discussion

The co-evolution perspective has not received significant attention in design education (Lotz et al., 2015). However, it would be beneficial if students were aware of co-evolution processes because the ability to frame problems and solutions through co-evolution is critical to an advanced understanding of design cognition and design metacognition (Ball & Christensen, 2019). Typically, co-evolution has been related to the ill-defined problems, where greater flexibility is to be found in the manipulation of the problem and solution spaces (Dorst, 2019). However, our study showed that the design teams also approached a well-structured re-design task by simultaneously exploring the problem and solution spaces. These detailed descriptions of the dynamics in which new design ideas are generated help practitioners recognize the key aspects of the problem–solution co-evolution process. Furthermore, this kind of re-design task, which presented constraints in terms of developing a new form within prescribed requirements, was a good exercise for practicing reformulation. However, the workshop setting and time limits might have constrained the students' approaches to designing.

In this study, we focused on the early stage of the problem–solution co-evolution process as consisting of specific problem-solving activities along with sketching. According to Self (2017), sketching is a potential driver for increasing solution-focused activity and in facilitating the iteration between problem definition and solution ideation. In accordance with this, we found that ideation and sketching were carried out simultaneously and in collaboration within all groups, even though the time used varied between the teams. Ideation and sketching usually occurred so that either one participant was sketching on behalf of the team while responding to the other team members' ideas in visual form, or other members were also drawing sketches aimed at improving ideas negotiated together. The students turned their attention to specifying their design in detail by constructing talking sketches. Two of the groups (G-interior and G-product) relied on the strategy of vertical sketch development. These groups worked with only a few design ideas, which were further articulated through constructing the prescriptive sketches. Contrary to G-interior's vertical sketching, sketching in G-graphic progressed in a horizontal manner. They produced many design ideas by generating several alternatives for the 3D form of the detergent bottle. A previous study (Seitamaa-Hakkarainen & Hakkarainen, 2000) highlighted that more experienced designers tended to consider only a few design ideas and then focus on developing and articulating them in depth. In this respect, G-graphic indicated novice-like practices by moving quickly from one design idea to another. According to Lotz et al. (2015, p. 45), "if educators want to encourage ideation of multiple solutions they need to teach bridge building between problem and solution spaces, but if they want to encourage the working through of ideas they need to emphasise parallel co-evolution."

The results indicate that G-product had the most intensive problem-solving co-evolution period. The creation of new 3D forms was based on intensive reformulation involving setting new problem expressions or modifying existing ones. Consequently, the students developed the ability to rapidly evaluate the design context and iteratively project promising possibilities. According to Crilly et al. (2009), product designers seek to resolve competing factors of both product form and consumer response such as drawing attention to the product, fostering recognition of the product type, generating attraction or desire, and supporting comprehension of function. Furthermore, the fundamental idea underlying designing is that design problems and solutions are explored in parallel from different stakeholder perspectives, including those of users. However, it should be noted that user-centered design methods, particularly in design practice based on the study of user experience, have been used in the teaching and learning of the product design students but are not extensively adopted in the other design disciplines in China. User-centered design, being the previous domain knowledge, helped the product design students adopt an end-user's perspective. Our results indicate that the other design students focused much more on the visual elements of the form than on user-related aspects such as usability. Despite the differences in the design activities, all three teams succeeded in creating a new 3D form of the detergent bottle that met the problem requirements. To conclude, it is important to improve students' understanding of the form of the product and the functionality of the proposed 3D model, for example, through analyses of usability and user-centered methods.

Conclusion

Developing professional design skills requires students to be able to perform a range of design tasks and learn to recognize various design constraints. Comprehensive co-evolution requires openness to the outside world beyond the original problem space (Dorst, 2019). Design students need to be guided toward questioning their design on different levels so that the design process can become more value-driven and user-centered rather than focusing only on developing the product's appearance. Our research indicated that it was challenging to implement this kind of broader view in the short workshop. However, from the viewpoint of design education, it is important that students practice various kinds of design tasks during their education, including well-structured design tasks that play an important role in scaffolding their design learning. In addition, design projects where students are initiated into the design process and provided models in their efforts to solve open-ended design tasks that include certain external design constraints and that take several weeks to complete play an important role in learning design practices. In design education, these projects have become progressively complicated as studying progresses, preparing students for professional practice, mastering embedded knowledge, tools, and skills, and gaining an embodied understanding of the "professional-way-of being" (Adams et al., 2011). This variation of design tasks requires *reflection-in-action* that characterizes the knowing and practices of skilled performers in design (Schön, 1983).

There is a need for future studies to deepen the analysis of problem-solving co-evolution between different design fields and professional experiences. Further research is also needed to understand 3D modelling and the role of user-centered design. For example, there is research on how bottle designs and rapid prototyping can be used as stimuli to collect users' emotional responses (Lee & Self, 2018). Rapid prototyping techniques are not used only for increasing the capabilities of product design students; they should also be taught in other design disciplines that train students in coherent rational activities in the industry design context.

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