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DIFFICULTIES IN TRANSFORMABLE DESIGN AND ITS CAUSES

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1. Introduction

Transformation is a phenomenon of transforming the existing configuration to a deployed one, or improves the present structure or functionality [Singh et al. 2009], [Liapi 2001]. Due to the obvious advantages and promising applications of transformation, the process has been used by various disciplines, such as architectural and civil engineering, mechanical, genetic, design and computer engineering. The society admired products that transform shape and functionality and used in various circumstances that have grabbed the attention of industrial designers in transformable design. Yet, designers have used transformation as a function facilitator in various products, for example a folding bicycle [Kitchen 2015], transformable chair [Leathead 2015], and smart cover for a tablet PC [Alesina and Lupton 2010]. Despite its practical and technical objectives, transformation is a source of fascination and act as a method of expression, for example kinetic art that express certain emotions [Parkes et al. 2008], and movement change and color arrangement [Hoberman 2004].
Designing transformable products is more complicated than static products, and thus it may be a hot issue in industrial design field. However, a very few design theorists have paid attention to systematic design methodologies for transformable structures [Skiles et al. 2006]. A successful product design is located in the middle of industrial design and engineering design [Horvath 2004], and hence it can be regarded as an interdisciplinary work by industrial designers and engineering designers [Kim and Lee 2010], [Eder 2013]. As such, the function 'transform' remains central to both industrial design elements and engineering design elements when it comes to design a realistic transformable product. To expand the scope of design and advances in identifying opportunities for transformable products, industrial designers should overcome difficulties in product design process for successful transformable design.
In our study, an effort was made to explore difficulties faced by novice industrial designers in the design of transformable prototypes, and present the causes of such difficulties to improve the design process.
To achieve this, we conducted a design experiment, wherein design-majored students were recruited to observe their transformable design activities with a same brief. We recorded their design activities with video and carried out short contextual interviews repeatedly. To analyze the data, we used protocol analysis method for verbal descriptions. The findings from verbal descriptions were analyzed to explore difficulties faced by participants in transformable design process and its causes were discussed.

2. Transformable design

Research on transformation has led the design community to define transformable design as a design field dealing with the development of products that show a state of change in their physical configurations and facilitate new functionalities or enhance the existing functionalities [Liapi 2001], [Skiles et al. 2006], [Singh et al. 2009], [Weaver et al. 2010]. Transformable products have multifunction capabilities that allow users to eliminate trade-offs between incompatible requirements, for example Strida bicycle [Sanders 1987] exhibits multiple distinct states based on geometry, materials and kinematics to facilitate mobility functions. As shown in Figure 1, a transformable chair called Exocet [Leathead 2015] is a long chair that provides various positions to sit or lie in various postures.

Figure 1. Examples of transformable design

Transformation in product design has several advantages, for example enhance use of space and material through functions sharing and the capability to change geometry. Moreover, an increase in flexibility and accessibility that comes from being capable to switch between certain moments is an important aspect of a transformable product [Weaver et al. 2010]. Besides its practical and technical outcomes, transformation sometimes acts as a method of expression. Kinetic art is an example of the application that expresses certain emotions. It is similar to the development of expression in art, from a static view (picture) to kinetic view (video). Some artists [Calder 1941], [Rickey 1972] have shown their art works of traditional sculptures by movement applications. Hoberman [2004] has designed Switch ball as a toy that transform its parts and change color when thrown.

The relationship between movement of transformation and emotion is also appeared in art fields, for example dancing expresses certain emotions by movement. This phenomenon has been supported by several researchers [Walk and Homan 1984], [Brownlow et al. 1997], [Camurri et al. 2003] to investigate the relationship between dance and emotions, where they revealed that a movement can transfer certain emotional effects to the viewers. Similarly, Nakata et al. [1998] and Häring et al. [2011] have investigated the role of body movements of a robot that draw intended users' emotions. Transformable design can also be a way of expression similar as product design aims to deliver good appearance as an expression of emotions.

Research on product design suggests that a design team should consider various elements very sensibly during product development process [Eppinger and Ulrich 1995], because such elements are interdependence [Evans 1959]. Therefore, it is crucial for designers to consider not only elements, but also the relationship between them. Hubka and Eder [2012] devised a technical system with external and internal properties for product design. External properties include function, aesthetics, ergonomics, cost, environment, and societal aspect while internal properties consist of elements of engineering design. Designing a transformable product is obviously difficult than a static product. Because, a transformable product has more design elements and the interdependency between each design element makes it more complicated. In general sense, a transformable product contains one or more components that move or physically separate from each other. However, most of non-transformable products have fixed components that cannot move or physically separate from each other. The phenomenon of transformation in products depend on the complexity of transformation (see Figure 2). By definition a simple pen with a cover can also be a transformable product. The reason is that it has a phenomenon of change of its physical state (closing /opening a cover) and facilitate a new functionality (mobility /writing).

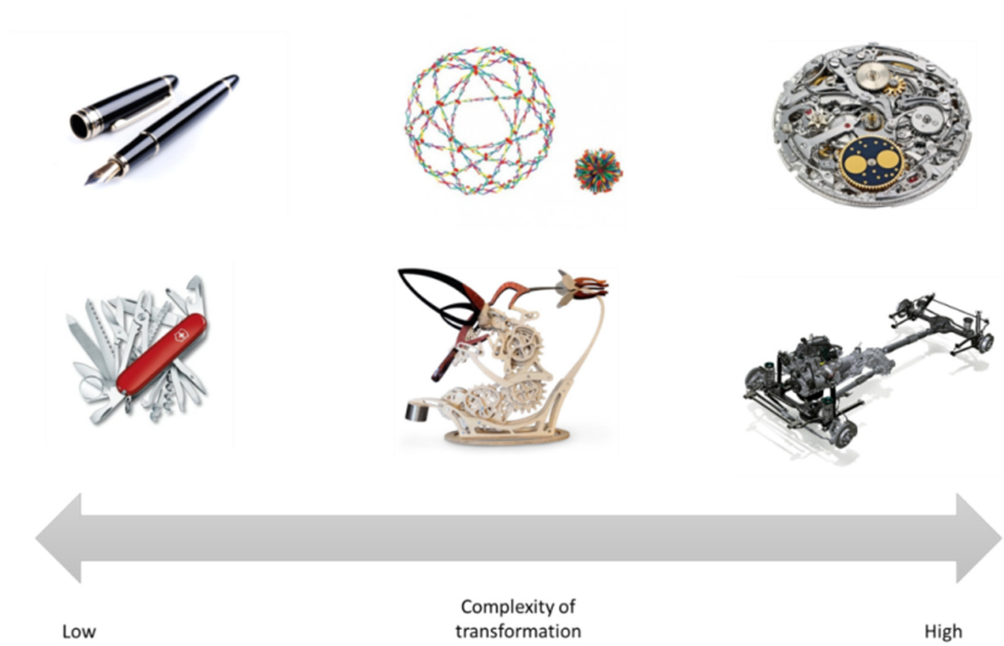

Figure 2. Examples of transformation

3. Methods

3.1 Experimental design

3.1.1 Participants

Four graduate students (Male = 3, Female = 1), ages ranged from twenty-two to twenty-six years from industrial design department were recruited. They had no engineering background related to transformable design and had studied industrial design in their undergraduate studies. They were divided into two groups based on their expertise. One group had to design prototypes while the other had to sketch (see Figure 3 as an example). During the experiement, design tasks related to transformable design were included just as to form concept design steps in the design process. Nevertheless various real problems in the design of transformable products can be occurred if the design process is realized as a working model. However, the objective the current study was to discover difficulties in the desgin process, therefore the success of each task was not evaluated, and hence no criteria was set for successful design tasks.

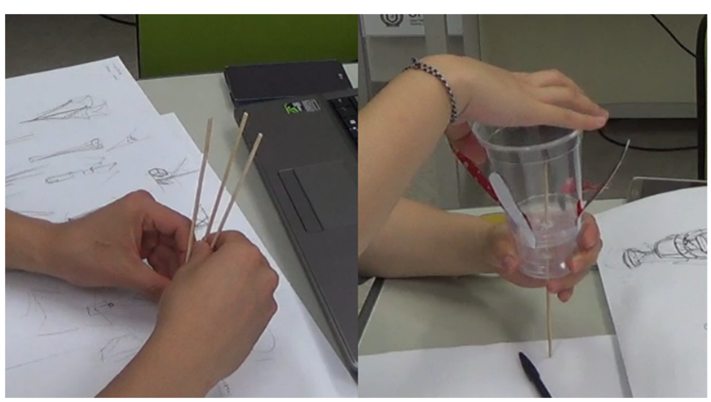

Figure 3. Example of prototype and sketches

3.1.2 Design tasks

To observe and analyze the design activities of participants, design tasks were developed with the following goals: first, if the intended task was easy, participants had to carry out design activities more efficiently, and if the task was difficult, they had to face difficulties in achieving the design goals. Secondly, they had to perform design tasks by including the elements of transformation. Based on this, they were guided to design a blossoming flower lamp as a design task by definning a proper level of difficulty with transformation scenario where the flower lamp was supposed to blossom by turning on using power. The difficulty level was determined by defining the number of movable elements required in transformable prototype. An object with only one movable element was considered as an easy level in the design process. Thus, the number of movable elements were increased in order to make the design process complicated to achieve a finest transformable prototype. In design task scenario, a participant was allowed to design at least two or more structures of revolving joint in certain parts to track the petal. Through this way, a petal required at least two revolving joint, a movable frame and an additional mechanism to move it. Moreover, if a participant would design an additional movement, it would need a more complex structure. Participants were allowed to use working principles along with other design elements, such as appearance, usage, and interaction. According to the type of flowers, participants had to design different forms and movement to influence the transformation mechanism, because each design element has interactivities between each other [Evans 1959], [Pahl and Beitz 2013]. As from above, it was expected to obtain data that indicate difficulties in the design process.

We also developed a design brief (see Figure 4) that includes the above conditions in order to instruct participants in the design of transformable flower lamp.

- Design a flower-shaped lamp that shows blossom movement (transform) when it turn on.
- Methods and tools for the design task are free. Whatever you want in the design tasks will be provided as possible.
- External information sources are acceptable unless you do not replicate.
- If possible, explain how the proposed lamp (product) design works.
- When you make a final outcome or failed to complete, stop the design process.

Figure 4. Design brief

The first condition provides task subject to the participants that is the design of transformable flower lamp. The second and third condition was applied to ensure a free environment that could be similar to the actual design practice. While, condition fourth restricted the minimum level of detail. Each participant was asked to describe the structure of the lamp upto their experience.

3.2 Research procedure

3.2.1 Experimental settings

Based on conditions in the task brief, the experimental settings were designed as shown in Figure 5. The experiment was conducted in a separate room and participants were allowed to use laptops with design toolkits, and internet connection. Moreover, sketching tools (i.e. A3 paper, sharp pencil, pen, marker), and prototyping tools (i.e. wooden skewer, form boards, utility knife, glue) were provided to the participants. In practice, the design environment to perform design tasks should be opened and unobstructed for the smooth usage of resources and methods. However, some studies suggest to restrict background variables to ensure the reliability of experiments [Leedy and Ormrod 2005]. In the present study, the design environment was arranged as similar to the actual design practice to avoid restricted variables, such as time, space, and method. A fully equiped design studio with various quality equipment (i.e. 3D scanners, plotters, printers, scanners, computers) was also provided to the participants.

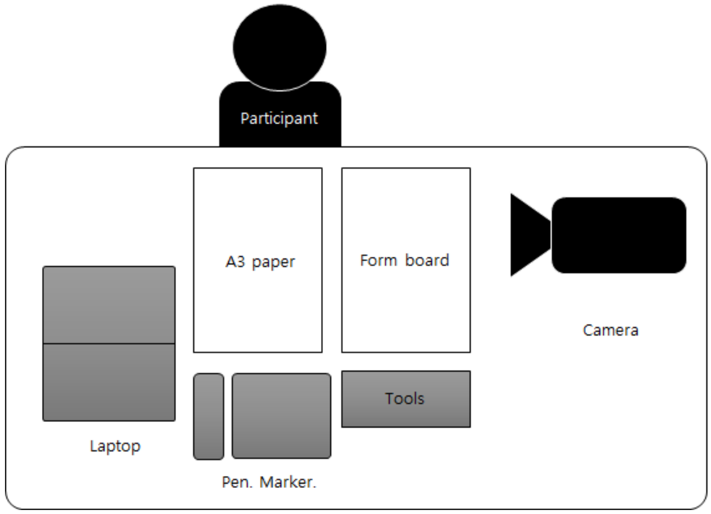

Figure 5. Experimental settings

3.2.2 Data collection

During the design process, we conducted contextual inquiries for every 10 minutes in order to make the design work productive and expand the scope of attention of partcipants in the design process. Each inquiry was quick and short to minimize the interruption. Participants were asked, (a) what is a particular difficulty in the design process? (b) what is your objective in the design of transformable prototype? (c) how your design outcome works?

With the aid of above, we obtained verbal data related to (1) difficulties in the transformable design process, and (2) participant's practice and methods they use to achieve the design goals. In the final stage, when participants had achieved their tasks, subsequently in-depth interviews were conducted. All design activities were videotaped and verbal data from contextual interview, videos, and sketches and prototypes that participants produced were collected.

3.3 Data analysis

We analyzed the verbal data related to difficulties in transformable design process as shown in Table 1, left column indicates verbal descriptions and its explanation in the right column. We also obtained data about the design process using task procedures.

Table 1. Signs of difficulties from verbal descriptions

Verbal description	Explanation
Difficult /Hard to /Cannot	Direct manipulated task difficulty which cause negative effects on the process
Do not know	Lack of knowledge and skills to perform design activities
Need to /Have to /Must	Necessary to do something, ‘something’ acts as a difficulty
Worry /Agonize /Concern /Think	Have troubles to generate/select ideas
May be /Would be able to	Show a possibility: Conversely, a participant cannot fully predict the effect of something
Want to /Wish to /Hope to	A participant suggests an objective, but unable to complete due to certain reasons
Misc	Other descriptions that indicate a difficulty as barrier to achieve objectives

4. Results and discussion

The following subsections present the result of each difficulty along with its causes. As we conducted the experiment in a naturalistic setting, therefore there were no specific data that can be quantitative.

However, we extracted the number of difficulties from the participants' interviews in order to expose the type of difficulties and their frequencies, and the time taken to complete the design process by each participant (see Table 2). Due to the research implementation, the number of design iterations or quantification of design decision was not considered, because the results merely focus on difficulties in transformable design and their root causes.

Table 2. Number of difficulties faced by participants

Participants	Difficulties					
	C1.1	C1.2	C1.3	C2.1	C2.2	Time
A	7	4	4	1	1	1:58
B	3	1	3	1	2	1:39
C	3	0	1	2	0	0:38
D	1	7	3	4	4	1:19

C1.1 = Lack of knowledge in developing working principles and mechanism for transformation
C1.2 = Difficulties in applying other working principles to the design process
C1.3 = Difficulties in movement prediction
C2.1 = Difficulties in interrupting component
C2.2 = Difficulties in considering properties of various phases in transformation

4.1 Difficulties in transformable design and its causes

4.1.1 Lack of knowledge and skills in developing working principles and mechanism for transformable design

The structure of working principle is necessary for transformable design. Elements involved in working principles act as transformation principles and facilitators [Singh 2009], and are required to design the inner structure (internal properties) of a transformable product. Howevder, participants in our study were novice in transformable design, specifically with limited skills to structure transformable systems related to transfer power from the motor to axial directions (subject case). As participant 'A' notes:

"I already determined the movements of each part. But, I think power transfer is the most difficult thing. I tried to conceptualize all this, but I do not understand how to transfer the power to each part, and I even do not know the name of the part which I want to use, but I think I am not able to progress the design. Participant A, 0:34:30".

Participant 'A' tried to find and apply a structure that can be narrowed and widen when rotated its one part to make blossom movement, but due to lack of knowledge about the mechanism 'A' faced difficulties in the design process.

4.1.2 Difficulty of application from other systems

Participant 'D' tried to employ the working principle of umbrella to design a structure that can be blossomed. Due to the difference between reference structure and target object, participant 'D' faced difficulty. Moreover, participant 'B' tried to apply the structure of a powder brush (see Figure 6). As 'B' notes:

"The brush is contracted when a user covered it. I reminded the motion of the brush and tried to apply it on the movement, but I think the petals are not diffused gradually. Participant B, 0:14:30".

Participant 'B' desired to design a flower lamp in which the petals were spread one by one when it turned on. 'B' prompted the working principle of a brush to narrow and spread each of its wires. For example, when a user covers the cap, the brush contracts. Otherwise, a user opens the cap and the wires of a brush may diffuse. However, the movement of the wires occurred at the same time which required additional design. As 'A' notes:

Figure 6. From original object to sketch

"I observed this flower. When it blossomed, the petals spreaded and revolved. I think the shape and movement has close resemblance with umbrella. I generated an idea that estimated the mechanism of the lamp. Participant A, 0:08:00".

Participant 'A' tried to bring up the working principle of umbrella. The transformation of umbrella is similar with the blossom of a flower. According to 'A', there is no idea I come up with to use the working principle of umbrella, because the structure is not appropriate to achieve objectives for the target transformable object.

4.1.3 Difficulty of movement prediction in a 3D space

When participants had designed transformable objects, at first they conceptualized the transformable structures. In fact, it is similar to the idea generation process. But, the prediction of movement in a 3D space is difficult. As the level of difficulty increases, the prediction becomes harder.

To overcome the difficulty that causes confusion, error and uncertainty, participants were allowed to use sketches and prototyping methods to confirm the validity of their ideas. It can be argued that prediction by imagination with a prediction by sketches has more enhanced validity. Participants had estimated the course of movement and composition of structures with line and shape on the sketches. However, it may also generate errors. More precisely, a valid method to confirm prediction is the prototyping method. By constructing and then testing the prototype models, participants could evaluate the validity of their own ideas. But, the validity is proportional to the amount of efforts involved in the design process.

4.1.4 The problems of using material space

In transformable design, each part of a product needs a space to be located. For example, an ordinary product has package and a space where inner structure can be placed. In transformable products, both external and internal properties use a space respectively, because they hold physical structures, mechanism and a space for movement. In case of static products, the connection of external and internal properties can be relatively fixed. A transformable product has moving and changing shapes of the properties. Therefore handling the space is complicated and somehow seems to be unpredicted. As participant 'C' notes:

"It is unreasonable. The gear itself is strange and the shape does not fit on it. Participant C, 0:35:30".

Participant 'C' used rack and pinion gears to transfer rotation movement in a linear direction in order to create a blossom movement as shown in the sketch (Figure 7, left). However, this mechanism needs a particular space which is marked with orange circles in Figure 7. Participant 'C' disliked its shape, because the gears may affect adversely the appearance of lamp, said participants 'C'. As participant 'B' notes:

"To fold petals to the point, this part must be elevated to a certain point. Then, to fully unfold, this part needs to go down to the same points. So, I made a leg, but I do not like it. I want to remove it. Participant B, 0:21:00".

From 'B' notes, the same problem was faced by participant 'C'. To facilitate blossom (transform), 'B' needs to add a moveable part that contains a vertical movement path. Because of the movement of this part, an additional space was needed for support leg, marked with an orange circle in Figure 7.
In comparison with ordinary static products, transformable design requires consideration about the space that necessary for the movement of the transformable products. In some cases, the elements related to physical appearance also requires a space which causes a collision between the elements, such as aesthetic elements and mechanical elements.

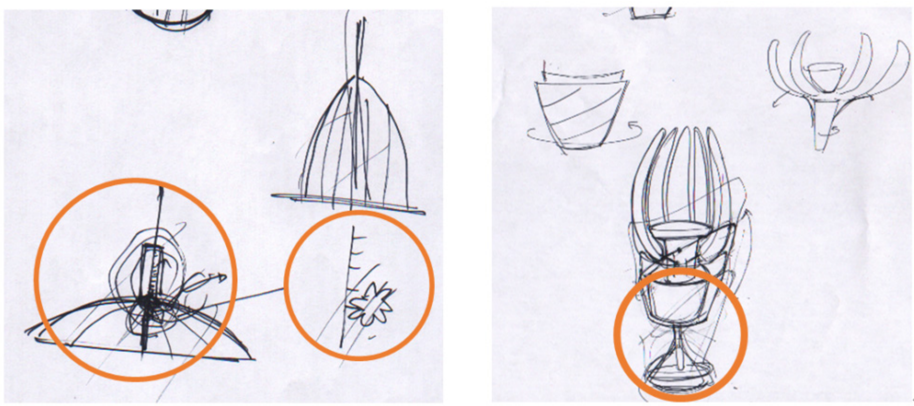

Figure 7. Sketch of participant 'C' and 'B'

4.1.5 Difficulty of design properties in various phases of transformation

Transformable design has various substantial states, because of the transformation. A simple transformable product may compose of at least three phases of transformation that need to be considered before, during, and after transformation. These features also require additional efforts. As 'A' notes:

"I think, if I designed the flower lamp, while considering only the shape at starting and ending point, it would be easier. I want to describe the detail movement of a blossom and try to test it, but it was quite difficult to design. Participant A, 0:51:00".

Participant 'A' faced difficulty of the middle phase in transformation process and hence, the design process was affected. In fact, a movement has 'course' and 'velocity' that act as variables of connectedness. During the design process, movement, shape and its elements in the procedure of transformation need to be considered. 'A' was required to consider not only the appearance of the object at a certain time, but also other physical features of the lamp in comparison with the object that has static appearance.
In sum, the findings from verbal descriptions of participants are categorized into two parts, firstly the difficulty of designing working principle (sections, 4.1.1, 4.1.2, 4.1.3) and secondly the mediation between exterior design and interior structure (sections, 4.1.4, 4.1.5). It implies that the difficulties arise from additional consideration of elements of engineering design. Owing to the interdependency among the design elements (interior and exterior), the mediation between external and internal properties is needed in the design process, because external and internal properties of product design often create a collision with each other which act as a barrier in transformable design process. Therefore, a successful design requires multidisciplinary approaches during the design process [Gericke et al. 2013], because design factors and variables are logically interdependent [Eppinger et al. 1994], which can disturb transformable design process.

5. Conclusions

We conducted a design experiment with four participants and analyzed their verbal descriptions using protocol analysis method to explore difficulties faced by participants in the design of transformable prototype. These difficulties include, developing working principle and proper mechanism, application from other systems, prediction of movement in a 3D space, the use of material space, and the use of design properties in various phases of transformation. The causes of such difficulties originated from limited knowledge and skills in the design of transformable structures, lack of clear and orderly imagination in idea generation process, collision of internal and external design elements and its interdependency, and phases of transformation. Moreover, transformable design is a new subject in design area that requires more interdisciplinary knowledge and skills from both industrial design and engineering design. The engineering part in transformable design includes, knowledge about mechanical structure, working principles and mechanical design skills, and predicts the movement of transformable structures. Besides this, knowledge about the mechanism of link work is also helpful in the design of transformable products.

In terms of methodology, we conducted the present study in a naturalistic setting by providing all possible requirements to the participants in the design of transformable prototype with no time limit, and thus the required tasks were coupled with participants' desires, when they realized that the design of transformable lamp was done. In most cases, design experiments conduct in a very conservative setting with limited resources that are required in the design process.

Limitations of the study emerge from the small sample size that holds novice participants in transformable design. If the experimental settings were applied over an adequate number of participants from several other design schools, we would hope to find the same findings and several different insights that would be helpful to infer an appropriate transformable design process. Future work will include behavioral inquiries to explore the influence of such difficulties to improve transformable design process. Then, it needs to be generalized by quantitative studies with enough number of samples. It is expected that the exploration of such difficulties in the design process can be a clue to establish a methodology or educational direction for transformable design. Through this exploratory study, we found several reasons and grounds for our future directions that include the development of transformable design recommender system that could provide and recommend appropriate guidelines and examples of transformation movements for novice designers and enable them to use transformation as a feasible functionality in their finished products.

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