A design ideation method for novice designers

Taegyun Kim

Submitted in accordance with the requirements
for the degree of Doctor of Philosophy

The University of Leeds

School of Mechanical Engineering

April 2020

The candidate confirms that the work submitted is their own, except where work which has formed part of a jointly authored publication has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

The work in Chapter 1 Introduction, 5 Systematic Brainstorming, and 6 Results of the thesis has appeared in publication as follows:

A Systematic Brainstorming Ideation Method for Novice Designers based on SECI theory, July 2019, Taegyun Kim; Alison McKay; Briony Thomas.

Taegyun Kim was responsible for designing 'a systematic brainstorming ideation method' by identifying novice designers' requirements from ideation methods, and implemented evaluation experiments for its validation.

The contribution of the other authors was providing comments and giving feedback during the overall development process. They also provided an opportunity for the evaluation experiment to be conducted in the United Kingdom.

Acknowledgement

I would like to sincerely express my gratitude to the people who have encouraged and supported me during my time at The University of Leeds in the United Kingdom. First of all, I greatly appreciate the hard work of my supervisors, Professor Alison McKay and Dr Briony Thomas, who provided professional guidance, constant encouragement, and open and frank discussions. This led me to establish individual abilities and a research area based on research strategies and interest. I would also like to show my sincere appreciation to Dr Vien Cheung who advised me to study at the mechanical engineering department and provided constant support during the PhD period.

I am extremely grateful to Professor Namjoo Joh at Korea Polytechnic University in South Korea, who offered me the opportunity to conduct evaluation experiments in Korea and provided constant encouragement. Junhyeok Choi deserves a special mention for helping me by demonstrating Perceptual Mapping Generation Software. Also, I must convey my thanks to Nicholas Thomas whose friendship and support enabled me to carry out my research with a better understanding of the UK and its culture. Of course, I hugely appreciate the participation of all the students that took part in the evaluation experiments, without whom this research would not have been possible.

Finally, I would like to show my sincere appreciation to my family, who have always encouraged and supported me. First of all, to my wife, Jieun Kwak, who has been by my side every step of the way, providing a sympathetic ear to hear my troubles, the best advice in my times of need, and never doubting me. And to the rest of my family, Hwangueum Kim, Geunwon Kwak, Kyunghwa Park, Soonhwa Park and Eunji Kim; thank you for your love and constant support. I dedicate this work to you all.

Abstract

Design ideation is a core stage in the design process that begins with a design brief and results in a range of design concepts from which solutions can be selected. The success of design ideation relies upon designers' creativity and ingenuity. In current practice, design ideation tends to be an ad hoc process which combines the designer's experience with techniques such as sketching, brainstorming, and mock-up to develop creative solutions in response to the brief. There are notable differences in ideation performance between novice and expert designers in that experts tend to follow a more systematic process, and have more experience and knowledge of previous designs to draw on. Design ideation is more challenging for novice designers who have limited experience on which to draw and no systematic process to follow.

This thesis provides a method that enhances the design ideation performance of novice designers by providing a systematic design ideation process for them to follow, and a database and associated visualisation method that gives them access to previous designs. The method was assessed through empirical evaluation experiments conducted with 101 students in the UK and South Korea. This confirmed that the method improves novice designers' generation of creative solution concepts in response to a design brief.

The research makes four contributions. The method, Knowledge-Enabled Design Ideation Method (KEDIM), provides a systematic design ideation process that includes three steps. The first step draws on a Database of Design Cases (DOS) that is supported by a database schema. DOS is a part of the research contribution that provides a structure to capture case data. DOS was validated through population with 540 design cases, and through use in the second stage of KEDIM, Perceptual Mapping Generation Software (PMGS). The core contribution of PMGS is its visualisation method that brings together selected design cases from the database and presents them in a way that enhances novice designers' abilities to draw analogies. The final contribution is Systematic Brainstorming (SBI), where these analogies are developed through a set of specific ideation themes alongside solution concepts. KEDIM, through these three tools, improves the effectiveness of novice designers ideation by increasing the number of solution concepts generated when compared with students not using KEDIM responding to the same brief.

List of Contents

List of Figures

List of Tables

Chapter 1 - Introduction

Design innovation has the capacity to improve quality of life by creating more useful and functional objects for end-users within society and companies. It enhances designs through incremental development of existing designs or radically through the creation of new services, and products through differentiation, decreased price, less time-consumption for end-users (Papalambros, 2008). Design thinking is a conceptual framework that supports designers in order to effectively bring these benefits of design innovation into their design processes. It is widely used by educators (Davis et al., 2016), because it provides a systematic process with the flexibility needed to create novel design innovations in response to design user needs. Design ideation is a key aspect of design thinking and comparable processes because it is where the new concepts are generated and developed. It is recognised that design ideation is challenging for novice designers. The accumulated amount of intensive working practice and learning is the key factor that establishes a systematic ideation process in accordance with the design brief and situation by employing and adopting appropriate approaches such as resource searching and development, and how they respond to difficulties in order to generate creative solutions (Ericsson, 1999; Ericsson, 2002; Kavakli and Gero, 2002; Cross, 2004; Hay et al., 2019). For novice designers, it is particularly challenging as they have limited experience on which to draw and no systematic process to follow. This thesis established a method that enhances the design ideation performance of novice designers by providing a systematic design ideation process for them to follow with a key aspect of novice designers' requirements which are reported from empirical experiments.

Design ideation is a crucial, early step in the design process that aims to explore, generate and develop solutions in response to a brief. It has a considerable impact on the overall success of the design process and outcomes (Moreno et al., 2015; Orthel and Day, 2016). An important role of the designer is to develop a range of design concepts (Moreno et al., 2015) from which solutions can be selected for further development. Despite its importance, there are limited tools available to support design concept generation, which primarily relies on the personal abilities of individual designers (Hernandez et al., 2010). It is widely recognised that novice and experienced designers behave differently during the ideation process (Ball et al., 1997; Ho, 2001; Kavakli and Gero, 2002; Kokotovich, 2008; Cai et al., 2010) with expert designers employing more systematic ideation strategies that build on their accumulated experience in order to achieve successful outcomes (Johnston, 2015). However, for novice designers, design ideation is especially challenging because they lack experience on which to draw analogies and have no systematic process to follow. In this thesis, the term ‘novice designers’ specifically means students designer. Section 2.3.2 differentiates between the ideation performance of novice and expert designers. This thesis introduces a practical ideation method that was designed with a view to improving the range and number of design concepts generated by novice designers in response to a brief.

1.1 Research background

The research wacs originally inspired by two factors: the growing potential of new manufacturing processes that enabled the realisation of shapes that, previously, were not producible, and the possibilities for designers to learn from nature using bio-inspiration. Emerging manufacturing technologies present opportunities and benefits that can be capitalised on within design. In particular, the development of manufacturing technologies is gradually enabling the production of forms that were previously difficult or impossible, and this has a particular importance as a key basis for opening up new design styles (Gao et al., 2015). Additive manufacturing technologies, including 3D (dimensional) printing, are representative of these emerging technologies. These technologies were initially invented to fabricate physical forms using successive layers of materials under computational control in the 1990s, and provided an alternative to the generally available tools based on subtractive processes, such as CNC, cutting, carving and others (Gibson et al., 2015). Considering when this technology was developed, it was applied relatively late to design cases with the expiry of many patents from around 2010 onwards (Gibson et al., 2015). The number of empirical design cases has been gradually increasing, and ranges are expanding from exploratory projects in art and prototypes to the consumer area. Some examples are given in Figure 1.1. These examples show distinctive design properties, and the seamless and complex form styles that were difficult or impossible to realise prior to the advent of 3D printing (Jonson, 2005; Anderson, 2012; Gibson et al., 2015).

Bio-inspired design is a form of analogy-based design and its popularity as a means of inspiring designers has grown in recent years. However, most of the literature reports design cases rather than methods that are suitable for use by novice designers. For this research, cases from bio-inspired design were used in the method development process. Numerous examples of bio-inspired design exist but are not collated in a form that can be easily used by novice designers. Some researchers, e.g. Vincent (2006), are developing classification schemes of bio-inspired system or methodology such as BioTRIZ. However, they are not accessible to designers because of their size and prior knowledge needed to use them.

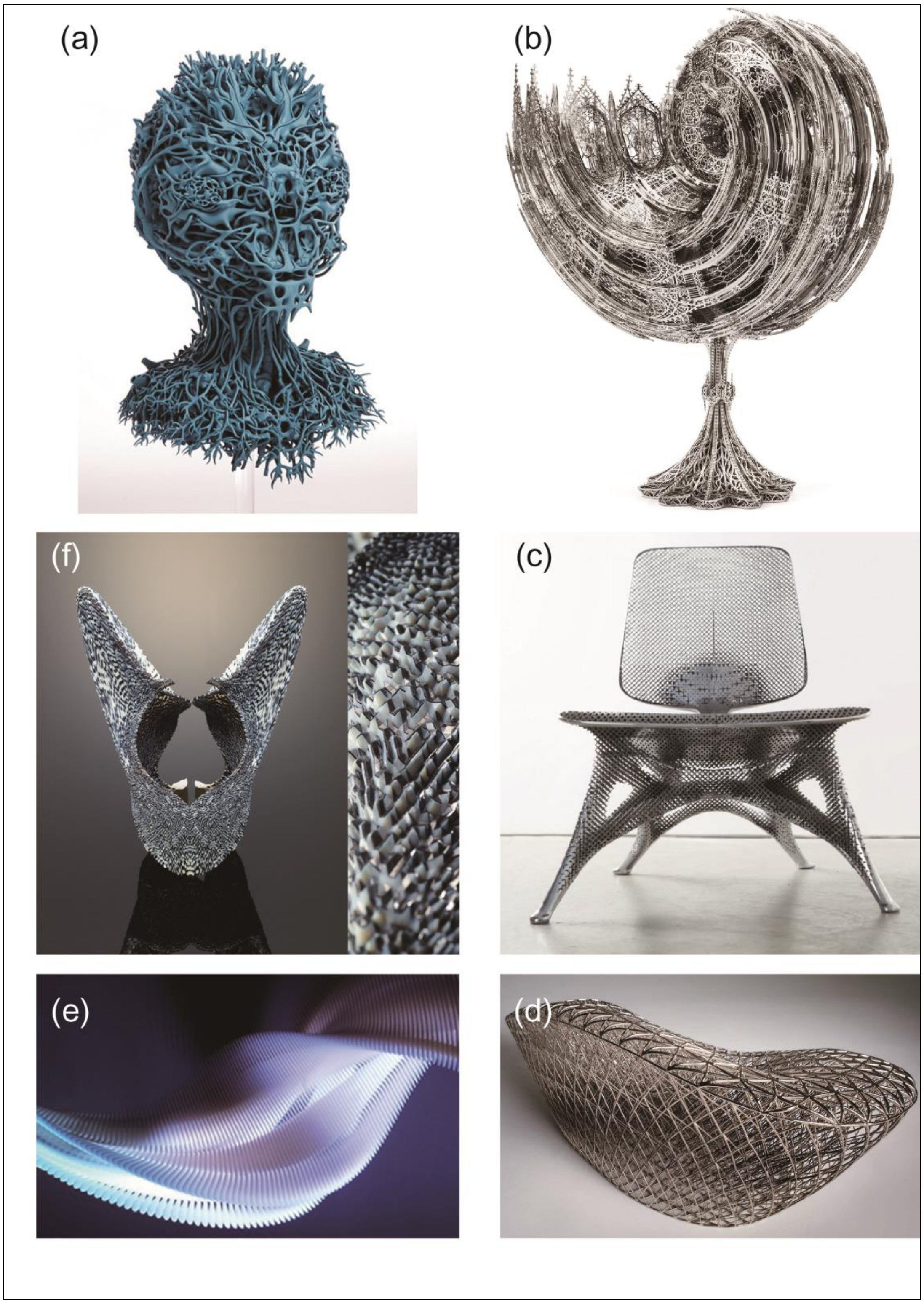


Figure 1.1 Design examples based on additive manufacturing technologies. (a) Eric Standley's "Agrieborz" in 2010, (b) Wim Delvoye's "Nautilus Penta" in 2013, (c) Joris Laarman's "Aluminum Gradient Chair, (d) Janne Kyttanen's "Sofa So Good", (e) Daniel Widrig's "Super Natural Motion' in 2013 and (f) Neri Oxman's "Doppelganger" in 2013.

A notable challenge with creating the aforementioned cases, such as those in Figure 1.1, was the development of comprehensive ideation strategies to understand and apply new or unfamiliar emerging technologies during design ideation (Johnston, 2015). Experts (designers, artists and researchers) mainly led these exploratory design projects, while few novice designers possessed the ability to do so (Johnston, 2015). This is because the experts had used their previous experience to establish their own unique ideation strategies and systems in response to the unexpected challenges faced (Cross, 2004). From this viewpoint, empirical research widely recognised that novice and experienced designers behave differently during the ideation process. A notable limitation of novice designers during ideation is that they tend to perform many concurrent actions with vague objectives (Kavakli and Gero, 2002), leading to an unsystematic overall ideation process which is ineffective to generate and broaden creative ideation solutions. These concurrent actions include searching design sources for inspiration, generating new design concepts, activities according to various situations, and the degree of organisation of actions (Ball et al., 1997; Ho, 2001; Kavakli and Gero, 2002; Ball et al., 2004; Dinar et al., 2015).

In particular, overcoming these differences in ideation performance is closely related to developing creative ideation performance in the education and practice of novice designers: in-depth understanding of emerging technologies, and mitigation of fixations from past experience (Anthoniw, 2013). Fixation is referred to as “an effect in which an individual might unconsciously focus on certain aspects of an object or a task, while leaving out other aspects.” (Vasconcelos et al., 2017, p.2) in the experimental psychology literatures. In the design process, fixation has significant negative effects on inspiration which is a key aspect of ideation, and often occurs during the diverse design activities followed by individuals, source searching, limited spaces of variations, and others (Moreno, Yang, et al., 2015; Vasconcelos et al., 2017). Anderson's workshop (2012) shows the challenges to generate creative ideas whilst exploiting the benefits of emerging manufacturing technologies. The theme was ideation of a pencil holder product with the aim of exploring the freedom of fabrication within additive manufacturing technologies. However, almost all of the designers generated timid outcomes because of a lack of creativity and cognitive fixation due to past experiences and tools. These differences enable assessment of current ideation methods and identification of the requirements needed to support novice designers’ ideation. These many differences also impact on how well designers obtain in-depth understanding and overcome fixations. Moreover, the importance of these fundamental and core ideation capabilities is gradually increasing in developing design environments, which will enable the fabrication of more seamless and complex forms.

With the aim of supporting novice (student) designers, previous research has appraised their ideation processes and found clues for solutions. In addition, methods have been developed but only a few common methods are used in education and practice (Shah et al., 2000). On the other hand, some experts of emerging technologies have claimed a need for an ideation method that enables effective creation of design concepts based on the benefits from these technologies for the purpose of their quick integration into products (Anthoniw, 2013). Empirical research demonstrates the differences between novice and expert designers within specific parts of ideation, such as drawing analogies (Kavakli and Gero, 2002), reviewing resources (Dinar et al., 2015), and ideation activities and strategies (Ball et al., 1997; Ho, 2001; Kavakli and Gero, 2002). These authors report on detailed professional comparative analyses, and the avenues chosen, but the identified benefits are not well integrated with ideation methods, and designers are only using limited, traditional ideation methods (Shah et al., 2000).

1.2 Aims and objectives

The aim of this research was to establish a method that could be used by novice designers to enhance their design ideation performance by increasing the number of design concepts generated (Ball et al., 1997; Ho, 2001; Kavakli and Gero, 2002). The following objectives were pursued.

1) To identify requirements for a design ideation method for novice designers through a review of current approaches to design ideation.
2) To propose an overall process architecture for a method that responds to these requirements.
3) To establish a database to capture bio-inspired designs and an associated visualisation method to enable novice designers to use them in analogy-based design from a range of sources.
4) To create an enhanced idea generation method that provides a structured approach to concept generation.
5) To evaluate the method with student designers.

The potential of the research is the identification of a systematic approach for improving the ideation performance of novice designers through common tools and findings from empirical research. The thesis discusses how a method can support novice designers based on understanding of their ideation and thought process, compared to experts. In this sense, the research provides an ideation method that support novice designers' creative processes, such as cognition, visual stimuli, and activities.

1.3 Outline of thesis

This thesis consists of seven chapters. This chapter provides an overview of the thesis, its aims and its structure. Chapter 2 outlines the relevant literature and provides a comparative analysis of the ideation processes between novice and expert designers, along with their utilisation of emerging technologies. Designers' thought mechanisms within the ideation processes are reviewed in order to identify the differences between novice and expert designers. The effectiveness of ideation skills, tools, and environments are also examined in order to assess the most appropriate ideation tools for novice designers' requirements. These are drawn together to form user requirements for the development of the ideation method introduced in this thesis: Knowledge-Enabled Design Ideation Method (KEDIM).

Chapter 3 provides a description of the research methodology used to develop KEDIM. KEDIM is comprised of three stages that provide a systematic ideation process architecture and an intuitive method of use. Beginning with an overview of the different types of Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009), this chapter explains how DRM was used to frame the research. Key research stages are clarified: method development, evaluation experiments, data collection, and analysis, and evaluated in accordance with research goals. The first stage of DRM (Descriptive Study I) is presented in Section 3.3. This aimed to identify the practice gaps between research and practical design environments in order to establish the design goals of KEDIM.

Chapter 4 introduces the first and second stages of KEDIM (Database of Design Cases (DOS) and Perceptual Mapping Generation Software (PMGS)), which were created in the second stage of the DRM (Prescriptive Study). The database captures bioinspired design cases in a way that allows them to be used as sources of inspiration in KEDIM. This chapter includes details of the database schema and its population with 540 cases. The transformation process from the database to the perceptual mapping is also discussed. These cases and data elements are visualised using PMGS which supports the drawing of analogies through the exploration of a large volume of design sources.

Chapter 5 outlines the third stage of KEDIM, Systematic Brainstorming (SBI), which is based on the four-stage knowledge generation model – SECI theory (Nonaka et al., 2000). This chapter outlines the development process from SECI to a set of specific ideation themes, and its implementation as a paper template and the establishment of usage guidelines. The development background, reasoning and combination process for use of brainstorming and SECI theory, and how it links with the first part of the ideation method are provided.

Chapter 6 reports the results of experiments with 101 design students in the United Kingdom and South Korea. Comparative analysis through observation and the assessment of ideation outcomes through questionnaire used, observation notes, and discussions are presented. In particular, the number of ideas generated within SBI was analysed in detail with respect of how well they reflected the design brief (motifs, design object, and manufacturing technologies), and systematically followed the ideation process. Finally, the data and results from empirical research are discussed. Following this, the limitations of the study, further development and future work are considered in Chapter 7 along with a summary of findings in relation to the research goals and conclusions are drawn.

Chapter 2 - Literature review

This chapter reviews the current ideation approaches and methods used by designers in order to identify the limitations, opportunities, and requirements for a method to support novice designers and enhance their ideation performance. The chapter begins, in Section 2.1, with a review of literature on design process and ideation with a focus on understanding underlying mechanisms of ideation methods, after which the evaluation criteria of designers' ideation process is provided in Section 2.2. This is followed by an assessment of ideation methods classified within Section 2.3 to evaluate how well they support novice designers' thought processes with the ideation process. The challenges and opportunities for emerging technologies to support ideation processes are presented in Section 2.4. Based on the limitations and opportunities identified in previous sections, the requirements for ideation that supports methods are proposed in Section 2.5, and the knowledge gaps are defined in Section 2.6.

2.1 Design processes

The term *design* is generally defined within the context of action(s) for development as follows:

1) "Transformation of existing conditions into preferred ones" (Simon 1996, p. 55).
2) "Design is about service on behalf of the other" (Nelson and Stolterman, 2014, p. 41).
3) "A product that is designed is designed to have particular function" (Madlener, 2011).

From this point of view and considering the current role of design, the objectives of the design process can be defined as moving 'from problem to solution areas', 'through identify to define', and 'ideate to deliver' stages (Simon, 1996; Dorst and Cross, 2001; Howard et al., 2008; Madlener, 2011; Dorst, 2011; Nelson and Stolterman, 2014). In practical design fields, design companies have established these series of stages as unique design processes in order to achieve the generation of creative solutions.

In order to identify the steps of a practical design process, design process diagrams were collected from official websites and documents which had been produced by leading design corporations or studios in diverse industries such as IDEO, Pininfarina, Frog Design Incorporation, and Design Work (see Figure 2.2). The website DEXIGNER, which is a database of design corporations, studios and organisations, was used to identify the leading design studios. General design process diagrams were analysed for grouping and classification of each step, which can be summarised as 'research – analyse – ideate – prototype – test – revision – output'. Figure 2.1 illustrates the conceptualised design process.

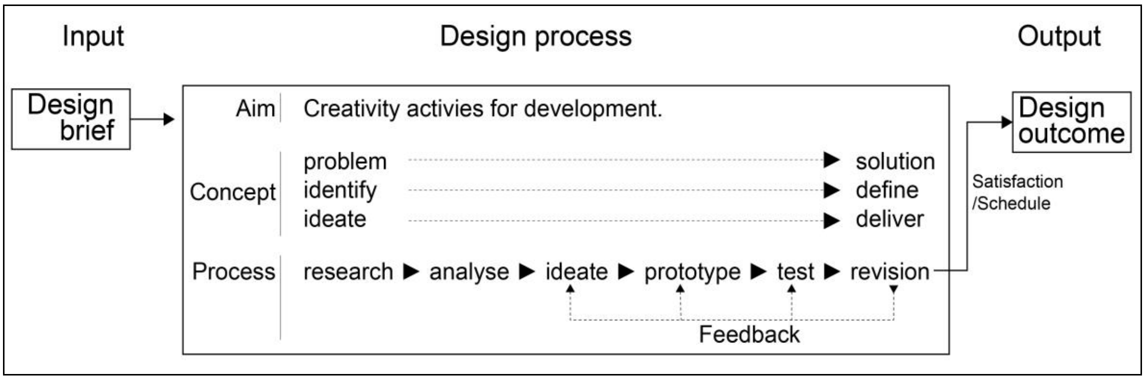


Figure 2.1 The concept of design process

In design processes, ideation is responsible for developing the initial solution concepts (Farel and Yannou, 2013; Moreno et al., 2015). The overall goal of design ideation is to generate novel or creative solutions in response to the design brief. The ability to generate ideas is a distinctive characteristic of designers, and the performance of the design ideation stage has a significant impact on the overall success of the design process and its outcomes (Moreno et al., 2015; Orthel and Day, 2016). In particular, design ideation is an important part of any design process because it is where designers use divergent thinking to generate design concepts in response to a design brief (Valkenburg and Dorst, 1998; Koronis et al., 2018). This stage is particularly prominent because the solution from ideation is closely linked to the success of design (Linsey et al., 2014). Ideation methods and their classification will be appraised in order to understand the current situation and identify limitations with respect of designers' thought mechanisms in the following Sections 2.2, and 2.3.

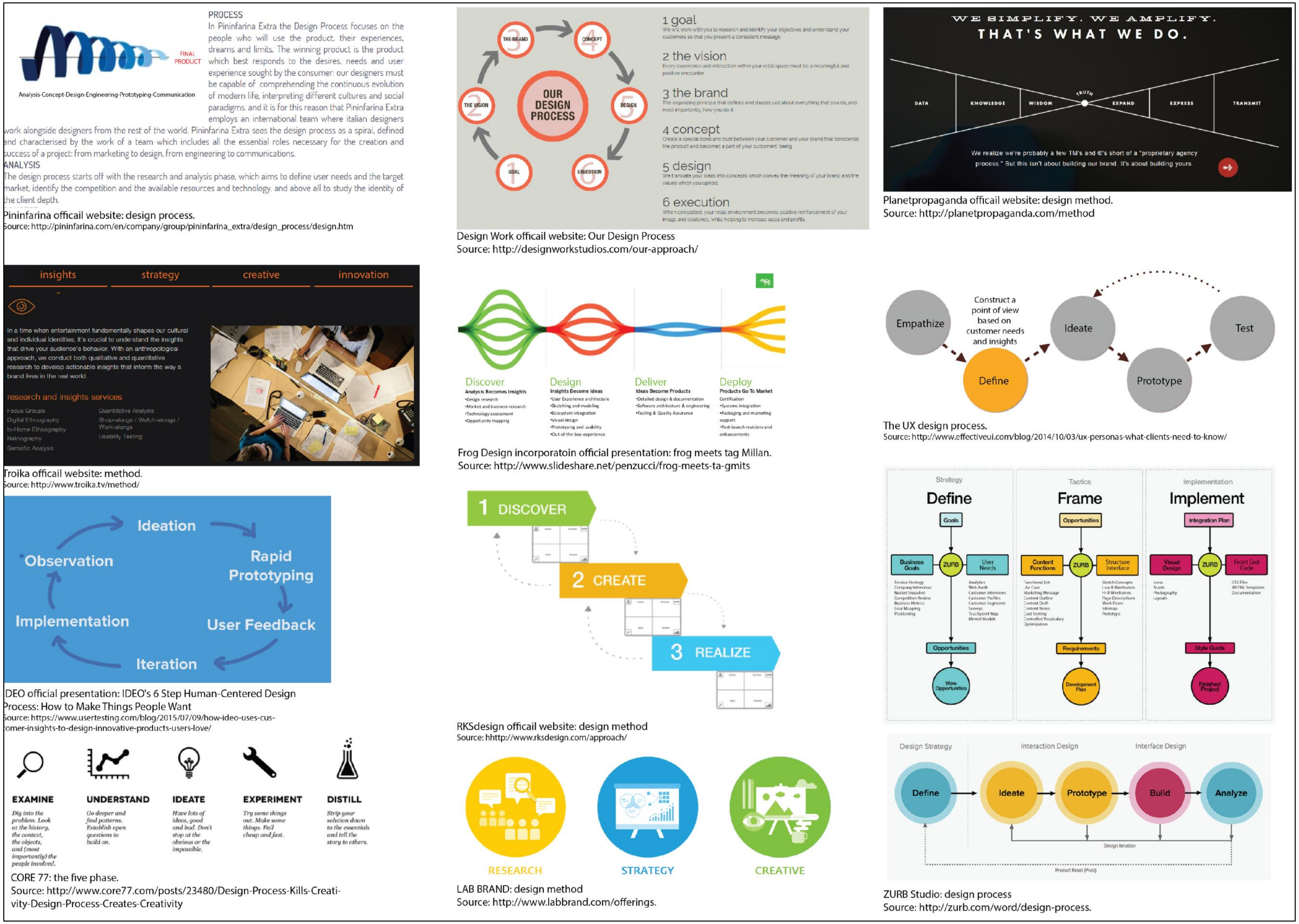


Figure 2.2 Examples of practical design processes

2.2 Ideation processes

The ideation process is the series of steps used to guide designers' thinking to aid systematic and/or effective ideation in order to reach creative outcomes according to certain criteria, such as actions or tools (El-Zanfaly, 2015; Piya et al., 2017). Beginning with understanding of ideation methods in Section 2.2.1, the classification of the ideation method is reviewed to identify requirements in response to the identified difficulties of novice designers in Section 2.2.2. This is followed by a review of the role of new and emerging technologies within ideation in Section 2.2.3. These findings are considered with respect to designers' thought processes in Section 2.3 in order to identify limitations, opportunities for improvements and the requirements of ideation methods for novice designers.

2.2.1 Ideation methods

Ideation methods aim to support designers' creative performance within the ideation process, and they reflect designers' thought mechanisms for understanding, refining, communication, or critical assessment of the ideation process for further development (reflection-on-action) (Jonson, 2005). The rudimentary ideation methods employed in education and practical fields are generally sketching and text (Jonson, 2005). Sketching reflects a designer's thought process and what they lean from external resources in an easy and intuitive way (Goldschmidt and Smolkov, 2006; Dinar et al., 2015), and textual information is used by designers to capture ideas and express detailed description that is difficult to record in other ways (Goldschmidt and Sever, 2011).

These rudimentary methods have been used for the purpose of developing ideation methods with the aim of providing enhanced performance and a variety of versions with brief guidelines such as thumbnail sketching, drawing, writing, and annotation (Jonson, 2005; Hopkinson et al., 2006; Orthel and Day, 2016). Furthermore, detailed instructions are required to investigate systematic ideation processes that users follow such as brainstorming, storyboarding, method 635, fishbone, TRIZ, or Shape grammar (see Table 2.1).

In the emerging digital environments, ideation development research has been exploring the application of relevant technologies to provide novel environments or functions. For instance, advanced technologies (3D scanner, Virtual-Reality, additive manufacturing technologies) have been used to provide digital environment user interfaces replacing conventional tools such as pen and paper.

This context indicates that the existence of diverse and intuitive ideation methods, and further research is required for the purpose of adapting to changing environments or utilising emerging technologies. However, it has been identified that designers are using only a few common ideation methods in education and practice despite diverse ideation methods existing and new methods with significant benefits being developed. As noted by Shah et al., (2000) "Despite several claims and much anecdotal evidence about the usefulness of these (common) methods, very little formal experimental evidence exists currently to indicate that these methods could actually be used … to generate concepts. Further, the rules and procedures for these methods seem to have been specified arbitrarily, regardless of the nature of the problem being solved." (Shah et al., 2000, p.377).

Research by Self et al., (2016) assists in identifying the cause of the limited variety of ideation methods used in education and practice. Four teams carried out ideation through drawing by hand, computer, and others. The research results show that drawing by hand was significantly preferred (77%, 56%, 87% and 58% for team A, B, C, and D respectively) (Figure 2.3.a and b). In particular, it is noteworthy that team A and B, which generated the highest number of ideas (around 400 and 300), used drawing by hand (77% and 87%). The major cause identified was 'a sense of heterogeneity' caused by required additional elements such as control of software and a different feeling compared to drawing by hand. These findings illustrate that designers prefer to use common methods due to intuitive method of usage, and the effectiveness of ideation performance also improved in accordance with the number of ideas generated. Unfamiliarity with new methods, additional requirements or differences compared to the commonly used methods are the major causes for designers reluctance to use them, and this decreases ideation performance. The following section will review the classification of ideation methods in order to identify the characteristics and limitations of commonly used ideation methods.

2.2.2 Classification of ideation methods

The classification of ideation methods provides an understanding of the benefits and limitations of diverse methods with comprehensive perspectives. In response to the identified limiting factor (that designers tend to use few methods), the classification of ideation methods enables the identification of the requirements for novice designers through comparison of their properties. The classification by Shah (2003), separated ideation methods into two groups, depending on the ideation process used: the logical method for systematic progressive stages or approaches, and intuitive method for supporting stimulation of inner mental process. Table 2.1 shows the classification of methods according to Shah (2003).

Table 2.1 Classifications of ideation methods

Main class	Sub classification
Logical method	Historically-based method: use catalogued in some form of database -e.g. TRIZ
	Analytical method: develop ideas from first principles by systematic analysis of basic relations, casual chains, and desirable/undesirable attributes -e.g. Inversion, and SIT.
Intuitive method	Germinal: aim to produce ideas from scratch -e.g. brainstorming, morphological analysis, and K-J method
	Transformation: generate ideas by modifying existing ones -e.g. checklists, random stimuli, and PMI method
	Progressive: generate ideas by repeating the same steps many times -e.g. method 635, C-sketch, and gallery method
	Organisational: help designer group generate ideas in some meaningful way -e.g. storyboarding, fishbone, and Affinity method
	Hybrid: synectics combine different techniques to address varying needs at different phase of ideation

Source: derived from Shah (2003)

Gao et al., (2015) highlighted the overall limitation of ideation methods. The ideation method that occupies a specific category (e.g. logical/ or intuitive) do not necessarily consider the correlation with other methods throughout the ideation process from the design brief to solution concept generation. Accordingly, the ideation process needs to combine both logical and intuitive methods in order to flexibly adapt to the designers' actual working process and environment.

Table 2.1 also shows that the majority of common ideation methods are positioned on intuitive methods, and a tendency was identified for creative concepts to suddenly emerge, rather than stem from a systematic process (Stones and Cassidy, 2010; El-

Zanfaly, 2015). On the other hand, they rely on an individual's abilities to gather ideas for concept solutions in a structured stage.

2.2.3 Emerging technologies and ideation

Emerging technologies present the opportunity for designers to increase the quality and novelty of design outcomes, yet they also present challenges for designers to understand new and unfamiliar technologies and integrate these with existing ideation strategies. Emerging technologies are making it possible to fabricate any form, and the role of designers within this changing environment will suit those with more advanced ideation capabilities and the ability to analyse and generate novel forms (Gao et al., 2015). In this light, the role of ideation is becoming significantly more important with the aim of generating creative solutions. According to the Royal Academy of Engineering (Anthoniw, 2013), in recent years, additive manufacturing technologies have established a hardware infrastructure for manufacturing free-form designs and complex form styles that could not previously be materialised with existing technologies. Existing ideation tools or ideation methods have however been found to be insufficient for generating free-from design style. Professor Richard Hague, director of the EPSRC (Engineering and Physical Sciences Research Council) Centre for Innovation Manufacturing in Additive Manufacturing at the University of Nottingham, stated that "Existing CAD systems are absolutely useless for exploring the design freedoms of additive manufacturing" (Anthoniw, 2013, p.15).

Fixations within the ideation process based on previous experience, education, and knowledge are one of the most fundamental problems for designers (Goldschmidt and Sever, 2011; El-Zanfaly, 2015). This is demonstrated in the Earl Grey Syndrome and pencil holder design workshop by Anderson (Anderson, 2012) showing the fixation of the designer's ideation imagination based on the application of new manufacturing technologies. Earl Grey Syndrome refers to the limitations of creative activities to correspond with emerging technologies and abilities. This term was coined from a dramatic scene in the television series *Star Trek*. Here the characters use a replicator machine which is capable of making anything from basic to unimaginably complex items. However, due to their lack of imagination the characters repeatedly use the replicator to make cups of Earl Grey tea. This symptom also presents itself in the area of design. Anderson organised an experiment to ideate a pencil holder product with the aim of exploring freedom of creation within three-dimensional printer manufacturing. Product design students and professional designers joined together and produced designs for their pencil holders. However, almost all of the final designs were timid variations of existing pencil holders. Anderson concluded from this that designers are mentally enslaved by past experience and familiar tools. In this light, it is necessary to identify the suitable ideation environment for increasing the quantity and variety of idea generation, using either conventional or digital environments. Research by Jonson (2005), Self et al. (2016), and Orthel and Day (2016) demonstrated that the conventional environments are significantly more suitable than digital environments.

Self et al., (2016) conducted comparative analysis about ideation processes using sketching in a conventional environment (paper and pen) and a digital environment (tablet and software). In the digital environment, participants felt a sense of heterogeneity because of the requirement for control of software and the different feeling this creates compared to the conventional environment, and these issues caused their thought mechanism to frequently shift between the problem and solution space with insufficient quality of results. Meanwhile, in the conventional environment, designers could generate sufficient quality of results in solution and problem spaces based on intuitive usage. In particular, Orthel and Day (2016) demonstrated how the number of ideas generated (quantity) are impacted according to the conventional and digital environment. Four teams conducted three sketching methods by hand (conventional environment), computer (digital environment) and others. As illustrated in Figure 2.3.a, hand drawing (blue colour) was the most commonly used method in the four teams (from 58 to 87 percent).

Furthermore, the two teams with the highest percentage of hand sketches (team A and C with 77 and 87 percent) generated a much larger number of ideas compared to the other two teams; the top two teams A and C generated approximately 400 and 300 ideas, and teams B and C around 50. An experiment by Jonson (2005) also shows similar results. Five design students and five practitioners in diverse areas (product, architecture, fashion, graphic, and general design) recorded ideation methods (text, sketch, mock-up, and computer) via self-report for multiple sessions. Figure 2.3.c which is a result of the first session shows the conventional ways were much more preferable than digital (S for sketching, W for words, and C for Computer): 70 percent were conducted in the conventional way (text, sketch, text and sketch), 20 percent in the hybrid way (text and computer), and only 10 percent using digital methods (computer).

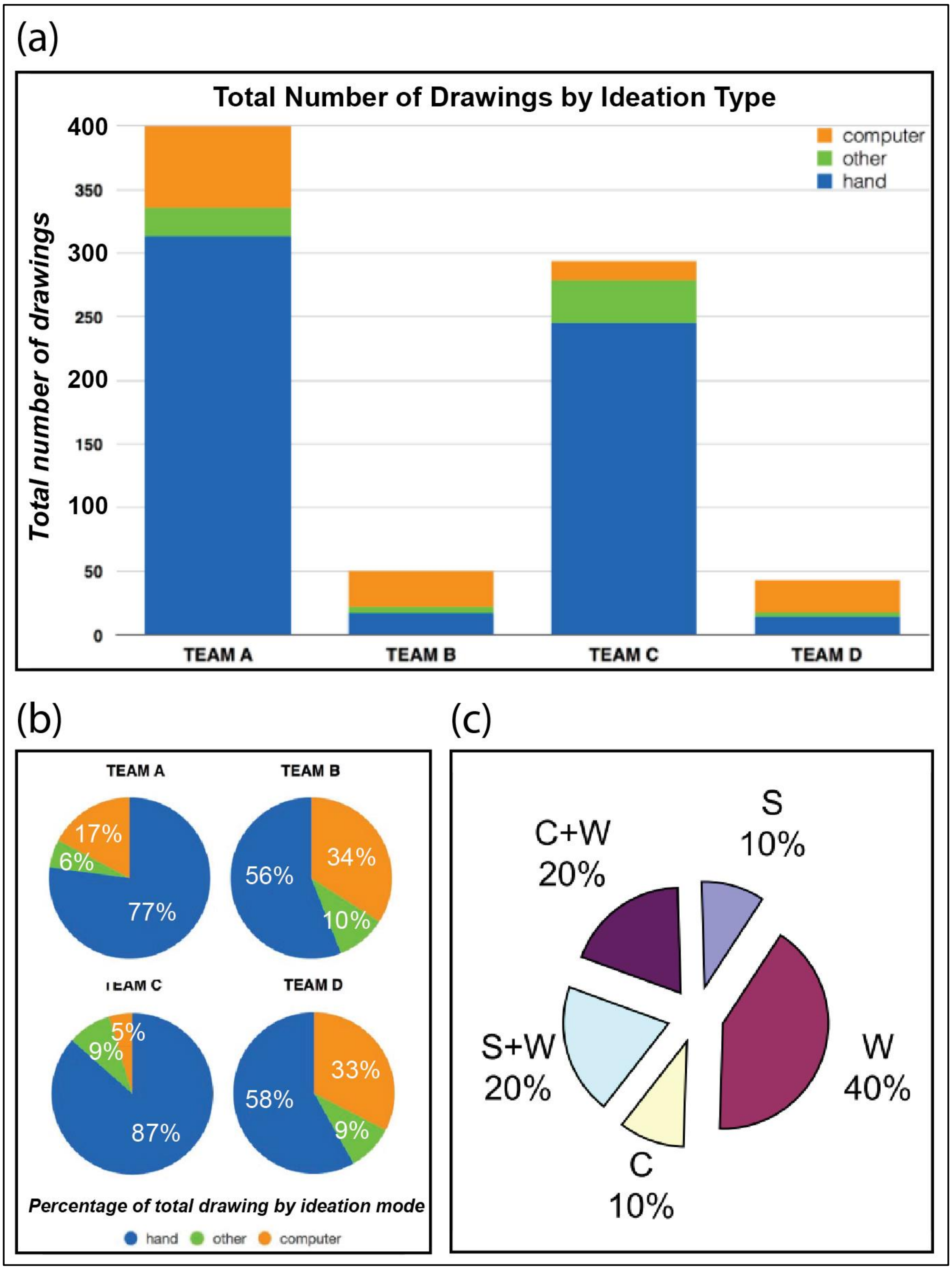


Figure 2.3 The impact of conventional and digital environments in ideation. Sources: (a) and (b) Orthel and Day, 2016, (c) Jonson, 2005

In summary, this research demonstrates that the conventional environment is the preferred environment for the ideation process using basic ideation methods. Designers are able to easily and intuitively express their thinking, and this enables the generation of a greater quantity of ideas and supports increased concentration during the process.

2.3 Designers' thought processes

In design, an understanding of underlying design process mechanisms supports better insights into relevant design cases. It also aids designers understanding of problem-solving approach and solutions, enabling them to better understand the appropriateness of the solution's proposed (Cash, 2018). Accordingly, an understanding of designers' thought process during ideation is a key consideration for the development and evaluation of ideation methods (Lawson, 2006).

Ideation is constructed with thoughts and their reflections (Dorst and Cross, 2001) over two stages (Nijstad and Sroebe, 2006; Wang et al., 2018). Firstly, designers look back at their long-term memory and reflect on problems, previous ideas, or other stimuli, search websites for reviewing existing cases, or have conversations with colleagues related to the design brief in order to refine coherent knowledge as a basic unit of designers' thought (Cross, 1999; Dorst and Cross, 2001; Orthel and Day, 2016; Koronis et al., 2018). Secondly, each coherent piece of knowledge is temporarily stored in the individual's working memory where they are reflected upon through transformation, combining, and adapting for true understanding of a situation, its problems and solutions (Romain and Bernard, 2013; Wang et al., 2018).

According to the type of thought, the designer's actions can be classified in four ways (Schön, 1983); 1. naming for searching and selecting the relevant features such as situation or problem, 2. framing for refining a core problem or solution, 3. moving for generating ideas or relevant actions with experimental attitudes based on naming and framing, 4. reflecting for evaluation to decide further ways that go back to framing or moving actions. These four actions can be used as coding in order to describe the designer's inner mental process (thought process activities) through scrutiny of their external expression. Observation-based research uses this coding to demonstrate comparisons of designers' inner mental process according to variables: the differences of behavioural patterns between two groups (Valkenburg and Dorst, 1998), comparison of the degree of sketching performance and level of attention according to conventional and digital sketching environments (Self et al., 2016), and analysis of the reasoning abilities and sketch representation between design students and non-design students (Self, 2017).

Key findings that informed this research were how the success of ideation relies on the designers' ability to shift thoughts from problem space (naming and framing) to solution space (moving and reflection), and focus on solution space (Self, 2017). The degree of external expression as design representation (sketching, making modes, and others) is the core for shifting with enhancement of indications or appositional reasoning (Self, 2017). The conventional environment (the paper and pen in case of sketching) is an easy and intuitive process, and increases intention. On the other hand, in the digital environment (the tablet in case of sketching) designers were interrupted because of software and hardware control issues (Self et al., 2016). The experiment by Valkenburg and Dorst (1998) demonstrated how inner mental mechanisms (problem space or solution space) impact on the inner mental process, external expression, and successful ideation outcomes in response to the design brief. Two teams with similar backgrounds developed a remote control robot to move as many balls as possible between two fixed points in three stages over eight days (stage 1. two-days for design, stage 2. five-days for building, and stage 3. one-day for competition). Analysis of the experiment highlighted that shifting timing from problem to solution space in the first stage (design during two-days) influences the effectiveness of ideation performance and a solution concept generated through sequential stages. At this stage, the winning team spent the longest time working (73%) within the solution space (moving), on the other hand, the other team spent the longest time working (49%) within the problem space (naming). These differences caused significant gaps in stage 2 building (external expression) in terms of further direction of thought and development, with the winning team focussing on testing and improving the stage 1 results through diverse actions: “choosing ideas, generation of ideas, considering arguments, integrating parts, evaluation of ideas, building models, detailing parts, consulting on interfaces, drawing the design, and evaluation of the design.” (Valkenburg and Dorst, 1998, p. 268). The other team, however, mainly placed the focus on “’choosing’ and ‘drawing’” (Valkenburg and Dorst, 1998, p. 267).

2.3.1 Thought mechanism in ideation

The overall thought process of designers can be described as solution-driven developments obtained through the iteration of mental activities and coherent expression: “the thinking process of the designer seems to hinge around the relationship between internal mental processes and their external expression and representation” (Cross, 1999, p29). The ‘Problem-design exploration model’ Maher et al., (1996) shows how each coherent piece of knowledge is connected, shifted and reacts in line with idea development (see Figure 2.4.a). According to this model, designer’s thinking can be divided into two spaces, problem and solution, and designer’s thinking flow drives the ideations in two ways; shifts between two areas for focus and fitness, and revision of the same areas for evolution.

Dorst and Cross (2001) suggested 'the co-evaluation of the problem-solution model' that is elaborated in the 'problem-design exploration model' (Maher et al., 1996) based on workshop observation (see Figure 2.4.b). To increase the probability of generating an ideal outcome, the thought process (problem and solution) together with continuous iteration of analysis, synthesis, and evaluation is much more important than first fixing problem and solution. In detail, the formed coherent information in problem and solution spaces shifts to become a core solution idea. After that, the core solution idea generated changes the designer's view about previously formed problematic information.

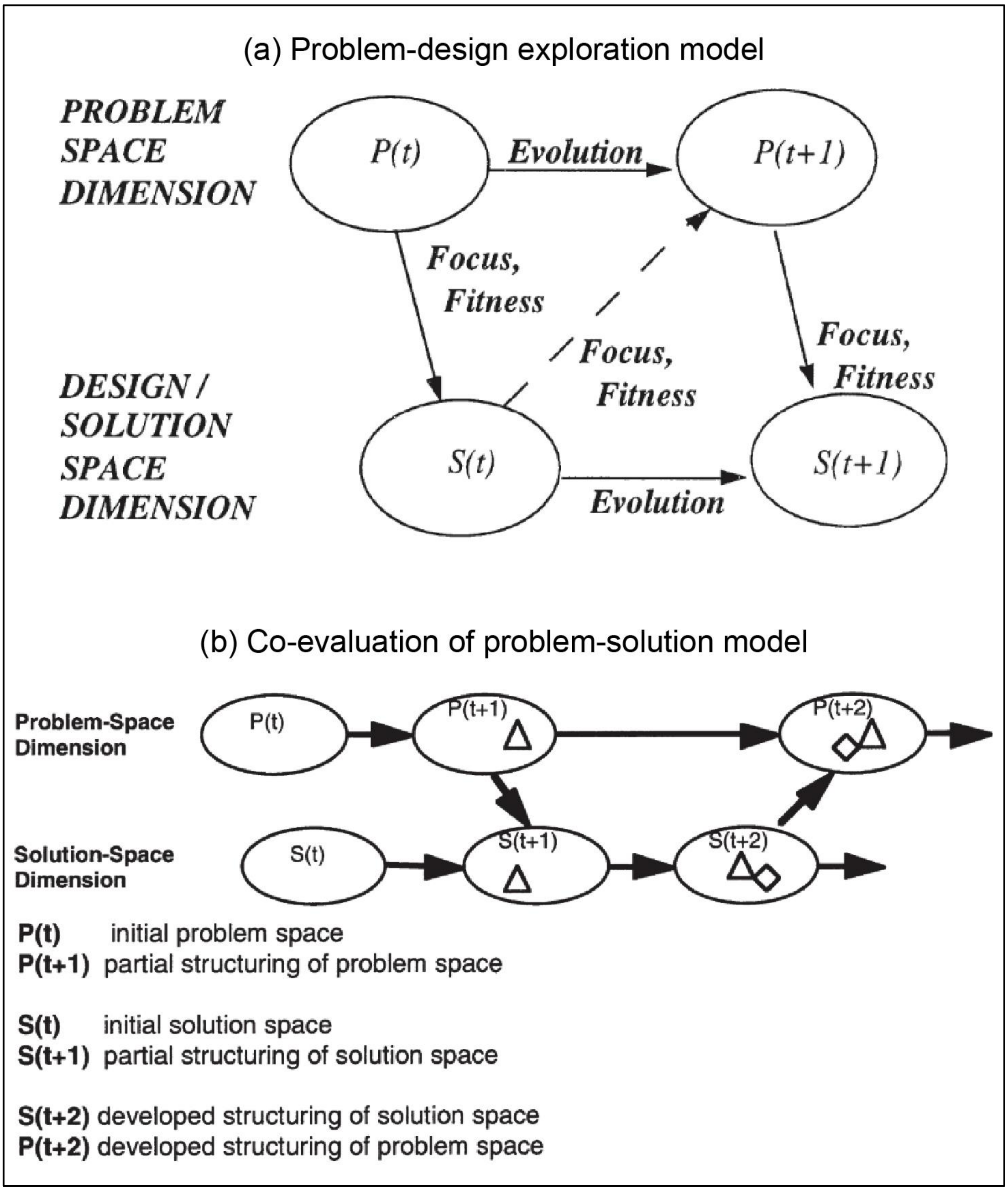


Figure 2.4 Designers' thought process models in ideation. Source: (a) Maher et al., 1996, and (b) Dorst and Cross, 2001

Figure 2.4 illustrates designers' thought processes (how their thought works and flows) during ideation processes: the sequential process through correlations between problem and solution-space dimension. With consideration of the limitation of methods which focus on a specific part of the process and lack consideration for other methods (Section 2.2), this property pointed to the main requirement: the need for systematic stages for the whole ideation process in order to improve the ideation performance of novice designers.

Empirical research identifies the major ideation stages based on designers' thought processes (Figure 2.4) that are reflected in their activities. Designers start ideation with stimulation, drawing on past experience, by reviewing relevant empirical cases and/or through research in response to the design brief (Koronis et al., 2018). Understanding and inspiration acquired during this stage are used to draw analogies and generate new concepts (Nonaka et al., 2000). The volume and quality of resources reviewed at this stage impacts the designer's ability to draw fundamental analogies and gain tacit knowledge (Goldschmidt and Smolkov, 2006). Tacit knowledge refers to the underlying core principle(s) obtained from a wide spectrum of cases as an effective ideation solution (Nonaka et al., 2000; Self et al., 2016) and is closely related to the degree of ideation effectiveness and the designer's abilities. The aforementioned findings provide the structured overall ideation process based on designers' thought processes comprising of three stages: review sources, draw analogies, and generate new ideas (Figure 2.5). It will be referred to as the 'ideation process model based on designers' thought processes', and is used as the basis to establish the method developed in this thesis. A number of such processes are available in literature; this one was chosen because it provides insights into the practicalities of overall ideation processes and so supports the identification of the requirements for ideation methods along with comparisons between novice designers and experts.

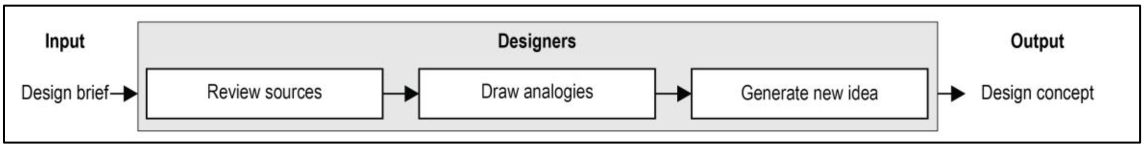


Figure 2.5 Ideation process model based on designers' thought processes

2.3.2 Comparison of ideation performance between novice and experienced designers

Identification of the key factors involved an experienced designer and understanding of the differences in ideation performance between novice and expert designers provides the requirements for ideation method development with novice designers in mind. Accumulated intensive working practice is the key factor rather than the learning of specific skills, tools or an individual's talent. According to Cross, the accumulated amount of deliberate practice is essential; "The attained level of performance of many types of experts,…, is closely related to their accumulated amount of deliberate practice." (Cross, 2004, p428). This practice needs to be undertaken for many thousands of hours with the aim of improving performance, motivation, and concentration (Ericsson, 1999; Ericsson, 2002).

Novice and expert designers tend to adopt different approaches to the ideation process (Kavakli and Gero, 2002). Empirical experiments identify the different style of ideation performance between novice and expert designers. Table 2.2 relates the literature on novice and expert designer's approaches to design ideation with the ideation process model shown in Figure 2.5. Experienced and novice designers usually employ different strategies in resource searching, how they respond to difficulties, and in developing a systematic ideation process (Hey et al., 2008). These differences affect the degree to which appropriate analogies are drawn from resources and utilised in idea generation. Overall, thinking styles and their variance, in accordance with external or individual situations and specific ideation stages, are the distinct differences between novice and expert designer groups. There are two main ways; depth thinking focuses on identifying the critical issues or information with the aim of defining essence as solution development, while breadth thinking treats almost every issue or piece of information on the same level in order to make groups or normalise. Their appropriate strategies are closely related to the successful problem-solving strategies (Ball et al., 1997). Experienced designers conduct each action with clear objectives that are well linked and structured accordingly (Kavakli and Gero, 2002). They search comprehensively with the aim of identifying implicit or abstract knowledge as valuable solution cues (Ho, 2001; Ball et al., 2004; Dinar et al., 2015), and develop a deep level of understanding across relevant areas (Self et al., 2016) in response to the design brief. If difficulties are encountered, they review the required information (Ho, 2001) or switch the ideation strategy from a breadth to depth first identification (Ball et al., 1997). On the other hand, novice designers tend to perform concurrent actions with vague objectives (Kavakli and Gero, 2002), and obtained information from research is often not well connected to their actions or practice (Self et al., 2016). The novice tends to commence with a depth-first search, reviewing all information at the same level, and in particular, overlooking the issue(s) that cannot be addressed (Ho, 2001; Dinar et al., 2015). This ideation process activities limits novice designers' understanding and ideation to surface-level cues from analogies (Ball et al., 2004). The aforementioned differences were also observed in the ideation process between novice and expert designer groups. If differences in the ideation process can be attributed to the accumulated amount of deliberate practice, it enables the refinement of ideation methods and definition of requirements in order to support novice designers to efficiently reach the required level.

Table 2.2 Comparison of novice and experienced designers' ideation process and abilities

		Experienced designers	**Novice designers**
Stimulation (Review sources)	Information searching (Dinar et al., 2015)	Breadth-first search	Depth-first search
	Information processing (Ho, 2001)	Identify quickly the most valuable issues and opportunities	Review all information on the same level
	Using information (Ball et al., 2004)	Obtain abstract knowledge from external relevant resources	Understand surface-level cues of design for analogies
Analogies & cognition (Draw analogies)	Reactions when faced with difficulties	Review the required information/knowledge (Ho, 2001) Switch the ideation strategy, from a breadth to depth identification (Ball et al., 1997)	Eliminate a problem (Dinar et al., 2015)
	Systematic process (Kavakli and Gero, 2002)	Well-organised and structured actions	Many concurrent actions with vague objectives
Implicit knowledge (Generate new ideas)	Cognition-obtained results (Ball et al., 2004)	Obtain abstract knowledge from external relevant resources	Understand surface-level cues of design for analogies

In summary, novice designers conduct concurrent actions with vague objectives, but also obtain results that are not well enough linked with each other to draw ideal outcomes. This analysis indicates that the major requirement of the ideation method for novice designers is guidance for overall ideation with deliberate practices as they can attain the expert designers' performance through the development of three key approaches: 1) research strategies cross relevant fields from design brief, 2) deep-understanding of problem and solution, and identify fundamental solution concept, and 3) ideation process and activities for high-quality and novel outcomes.

2.4 Evaluation of ideation effectiveness

In design development processes, ideation is responsible for developing initial solution concepts (Farel and Yannou, 2013; Moreno et al., 2015) from which the final design is developed. The overall goal of design ideation is to generate novel or creative solutions in response to the design brief. The ability to generate ideas is a distinctive characteristic of designers, and the performance of the design ideation stage has a significant impact on the overall success of the design process and its outcomes (Moreno et al., 2015; Orthel and Day, 2016).

A design idea is a solution created by a designer in response to a design brief. Individual ideas include analogies and notions of how the solution will function, how it will respond to the brief and how it might be realised (Fu 2014). Individual ideas are reached through designers' actions, reactions and conversations, and derived through sketching (Schon and Wiggins, 1992). Design ideas can be classified in two ways. Type 1, P-creativity (P for psychological), stems from the mind of the individual concerned. Type 2, H-creativity (H for historical) is derived from previous history (Boden, 1998). From these two types of inspiration sources, designers collate relevant experience, understanding, information, and assumptions in order to create various ideas for problem framing, interpretation of issues (data analysis, scenario, specific situation), and solution development.

Yang (2003) highlights a number of challenges in assessing the performance of design ideation processes. However, many authors also recognise the importance of acquired information to the quality of design ideation outcomes. Indexing, searching, and classification are commonly used as information search strategies with the aim of providing better understanding of individual designers' ideation activities and linkage with creating a successful outcome. Wide-range indexing, searching, and classification of information clarifies relevant but ill-defined ideation issues, and this supports researchers to clarify designers' properties with specific perspectives (e.g., ideation activities in accordance with working experience, specific environments, or controlled situation), or assess newly developed ideation tools or methods based on in-depth understanding of designers' ideation activities, (Maher and De Silva Garza, 1997). Ahmed et al., (2003) carried out searching and indexing of 12 participants from 2 hours of audio recording. 18 types of ideation process were identified based on 8 indexed design activities (consider issues + aware of reason, consider issues + refer to past designs, aware of reason + refer to past designs, aware of reason + question is it worth pursuing, question is it worth pursuing + refer to past designs, refer to past designs + use intuition, refer to past designs + find a different problem, and lack confidence in own decision + use trial & error). This data highlights the difference in ideation performance between novice and expert designers. Creating a novel solution through application of emerging technologies, such as additive manufacturing technologies, is one of the major challenges for designers because of lack of experience and fixation. Lauff et al., (2019) introduces indexed and classified information of additive manufacturing technologies through a set of 27 cards - each card presents specific indexed information with a structured template (textual description, before and after image description, pictures for real-world scenario) within four categories (product, business, design process, and printability principles of designing). Overall, participants evaluated this method as being extremely helpful to aid understanding of the concept of additive manufacturing technologies and its application in ideation processes.

With consideration of indexing, searching, and classification for ideas, Shah (2003) proposes four metrics to systematically assess design ideation performance: the total number of generated ideas (quantity), how well ideas correspond to the given design brief (quality), how many solution spaces were explored (variety), and how many unexpected solutions were ideated compared to other cases (novelty). This evaluation method has been widely used to understand and assess the effectiveness of ideation methods or empirical experiments with respect of idea representation, stimulation, analogies, and creativity (Linsey et al., 2011; Chan et al., 2011; Sarkar and Chakrabarti, 2011; Venkataraman et al., 2017). Gray et al., (2019) introduced an ideation tool for novice designers to address the specific situation in which ideas are exhausted, and Shah's metrics were used to evaluate this tool. This study also normalised the participants' characteristics, particularly the large range of designers' ideation performances, according to the analogical distance between the design brief and information obtained, and defining the role of novelty within design creativity (Jagtap, 2019; Jia et al., 2020). The degree of successful outcomes in shape-based design activities was also clarified within consideration of the virtual and real environments, along with relationships between cognition and activities (Filippi and Barattin, 2019).

Numerical methods are based on comparisons between the experimental and control groups. Cohen's kappa coefficient is a commonly used method, and provides precise assessments of agreements between two users because it considers both the percentage of agreement and its actual situation (Tang et al., 2015). In this sense, design researchers dealing with creative idea generation, analogy, inspiration and fixation are using these kinds of assessment methods (Linsey et al., 2011; Linsey et al., 2012; Wiltschnig et al., 2013; Vasconcelos et al.ss, 2017). Observations from specific perspectives have been frequently used with the aim of identification of clear cues from data collected or in accordance with research goals. Varied themes for observation optimise research background, such as experiment environments, the number of participants, or participant type (individual or groups). It is possible to observe comprehensive actions and communication of participants with the aim of finding cues and clarifying their response when establishing their desire to use tools, a method previously developed, or a specific situation. The ideas generated through sketching and writing are also observed to provide insight into participants' thought mechanism and its development process. These observations are recorded through notes, marking, or counting the number of ideas with specific perspectives for analysis. The experiments combine these evaluation methods or use in partly in order to design optimised data collection and its analysis followed by indexing, searching, and classification for ideas in response to their research objectives and experimental environments. Yang (2003) used assessment tools alongside numerical formula, and observation together (the number of ideas generated, timing of concept generation associated, type of sketching, and influences from designer's prior experience) in order to identify the complex correlation between the concept generation process and the degree of successful outcomes. Lauff et al., (2019) developed design principle cards in response to support novice designers' understanding and utilisation of additive manufacturing technologies during the design development process. This research used partial measurement metrics by Shah (2003), quality and novelty of ideas generated, based on data from 61 participants.

Effective measurement criteria are needed to provide the clear and specific objectives for the method being developed, and lead to effective development and evaluation processes (Blessing and Chakrabarti, 2009). According to Shah (2003), ideation effectiveness can be measured by evaluation of ideation processes and outcomes from four perspectives: the total number of generated ideas (quantity), how well ideas correspond to the given design brief (quality), how many solution spaces were explored (variety), and how many unexpected solutions were ideated compared to other cases (novelty). This evaluation method has been widely used to understand or assess the effectiveness of ideation methods or empirical experiments with respect of idea representation, stimulation, analogies, and creativity (Linsey et al., 2011; Chan et al., 2011; Sarkar and Chakrabarti, 2011; Venkataraman et al., 2017).

The linkage of four metrics (quantity, quality, variety, and novelty) by Shah (2003) are illustrated based on ideation process and outcomes: ideation performance focusing on 'quantity and variety' closely influence the 'quality and novelty' solution concept generation (Laing and Masoodian, 2016). This is because ideation processes achieving quantitative and varied ideation enhance users' in-depth understanding about problems, solutions and the design brief, and so overcome fixations (Venkataraman et al., 2017; Borgianni et al., 2018). A number of experiments also describe these situations from workshop observation: "groups using the multiple dialogue treatment generated more unique ideas…, more high-quality ideas…, and more novel ideas." (Dennis et al., 1997, p.208), and "more ideas give rise to more good ideas." (Reinig and Briggs, 2008, p.403). These descriptions clarify the importance of designers' ideation performance focusing on the total number of ideas generated (quantity) and how many solution spaces were explored (variety) for the purpose of ideal solution concept generation (novelty and quality). These measurement metrics of ideation effectiveness (Shah, 2003) and their relationship were used to identify requirements and establish concepts for the ideation support method proposed in this thesis.

2.5 Requirements for ideation support method

The previous sections highlight the limitations and requirements of ideation methods with respect to key differences between the ideation processes of novice and experienced designers. Accordingly, literature reviewed identified three key issues that should be considered in method development design with respect to desired abilities of novice designers as below.

Issue 1. Disconnected ideation methods. The majority of ideation methods used or developed focus on specific parts of the ideation process, and lack consideration for the relationship or correlation with other methods (Gao et al., 2015). Ideation methods and their procedures tend to be arbitrary in regards to concept solution generation in response to the brief (Shah et al., 2000).

Issue 2. The lack of a method that can support the design of the whole ideation process with appropriate methods and orders. An extension concept of ideation methods seems to be necessary; designers can enhance abilities to select and combine suitable ideation methods in perspective of the whole process to reach a better ideation process and outcomes.

Issue 3. Regarding the form-generation stage the ideation methods seems to mainly rely on personal abilities with analogue and/or traditional approaches. For instance, TRIZ and brainstorming, which are representative of logical and intuitive ideation methods, focus on the systematic functional development strategy and sequential generation of ideas and relevant issues, and introduce the form-generations that are related to creativity as personal features.

In addition, the papers that deal with emerging technologies in ideation were reviewed and assessed to understand how they well correspond to the aforementioned issues as an expanded exploration of emerging technologies in 2.2.3. The results demonstrated that the majority of research aimed to develop an ideation tool to provide improved working environments, but on the other hand, there were no concerns about how to support designers' understanding for use of the emerging technologies and applying the benefits of them into ideation outcomes, as described in Table 2.3. This gap illustrated the aforementioned limitation of 'a sense of heterogeneity' from required additional elements (use of method, and tools). In summary, designers are currently facing the difficulty of how they understand the emerging technologies and overcome fixations in order to generate novel ideation outcomes.

Table 2.3 Context of Ideation researches for emerging technologies

Research objective	Used emerging technology
Modelling software for advanced design ideation process and design style (Huo et al., 2017)	Touch screen, 3D scan and Virtual Reality
Explore the novel design ideation process and software with utilisation of 3D scanner. (Piya et al., 2016)	3D scanner and customised software
Software for new 3D design style; setting the centre of gravity of physical object which is fabricated by 3D printer (Prévost et al., 2013).	Customised software
Modelling software for supporting decisions in team projects (Piya et al., 2017)	Customised software
Explore advanced 3D forms based on the additive manufacturing technologies (Ou et al., 2016)	Additive manufacturing technologies
Exploring the latest 3D forms for heat exchanger to increase efficiency (Ventola et al., 2014; Langnau, 2016)	Additive manufacturing technologies

Based on the issues identified, three requirements for the ideation support method were established in order to improve the effectiveness of the ideation performance for novice designers: 1) a systematic ideation process from design brief to concept solution generation and 2) stimulation through a greater quantity and variety of resources, with 3) a designer-friendly method.

Requirement 1: A systematic ideation process is required to provide structured idea development during the ideation process from the brief to solution concept generation. The majority of methods concern specific parts of the ideation process, and they are disconnected with others (issue 1). This situation is challenging to novice designers. As outlined in Section 2.3.2, they have limited experience on which to draw and no systematic process to follow. Furthermore, they are prone to carrying out inefficient ideation compared to experts - narrow information searches, evasion of difficulties, and unfocused objectives. Research on the effects of fixation in idea generation has also noted the importance of inhibiting spontaneous design heuristics and following a generative reasoning process (Cassoti et al., 2016; Houdé and Borst, 2014). When compared with the process employed by experienced designers, it is evident that the novice designer would benefit from tools that support a structured ideation process and inhibit spontaneous solutions, in order to mitigate limited experience and know-how (Kavakli and Gero, 2002; Dinar et al., 2015).

Requirement 2: Stimulation through a greater quantity and variety of resources. The resources relevant to a design brief, such as case studies consisting of text and images, assist designers in understanding previous design solutions and results. As the quantity of resources increases, the level of stimulation also increases and a greater depth of understanding is achieved (Goucher-Lambert and Cagan, 2017). Furthermore, developments in design theory, in particular design as a generative process (distinctly different from decision-making or creativity), have noted the role of knowledge structures as a condition for generativity (Hatchuel et al., 2018). A higher degree of stimulation and knowledge may be achieved from a greater variety and a larger number of resources to better support designers in overcoming fixations, enhancing the creativity, quality and diversity of outcomes (Venkataraman et al., 2017; Borgianni et al., 2018).

Requirement 3: Ease and intuitive method of usage: Designers are using only a few traditional ideation methods, and very few new methods are actually used in practical fields (Shah et al., 2000). In regard of this gap, Section 2.2 indicated that minimising the 'difficulty of use' and 'sense of difference' needs to be addressed at the method design stage with consideration of approaches such as method of usage, concepts, technology used, or environments. For instance, a number of studies have suggested guidelines or methods to resolve the difficulties that novice designers encounter within the ideation process (Goldschmidt and Smolkov, 2006; Orthel and Day, 2016). Despite these efforts it is difficult to find empirical evidence that designers are using the identified methods.

These requirements were used to drive the development of a design ideation process method. The detailed development of this process will be introduced alongside the research design in Chapter 1.

2.6 Summary

This chapter has reviewed available ideation methods along with classification and analysis of empirical experimental results in order to identify the limiting elements with respect of novice designers' ideation performance. The chapter analysed the relevant literature for the purpose of establishing the requirements of ideation methods for novice designers and a multi-dimensional evaluation method.

Designers tend to mainly use rudimentary ideation methods in education and practice, despite new methods having been suggested for the purpose of improving ideation performance in accordance with a specific situation, environment, or objectives. Empirical research identified that the major cause is 'a sense of heterogeneity' from required additional elements and the different environment, and a significant difference in ideation performance was observed in accordance with the number of ideas generated (Jonson, 2005; Gao et al., 2015; Orthel and Day, 2016).

The review of the classification of ideation methods model (Dinar et al., 2015) illustrates that commonly used rudimentary methods belong to the intuitive method category, and few methods are categorised in the logical method category. Intuitive ideation methods support idea generation through various processes, however, it is not specified how designers generate ideas with consideration of previously generated design concepts. In particular, methods mainly rely on designers' individual abilities for form-generation. The majority of ideation methods also fail to consider correlation with other methods, and do not provide a systematic ideation process or a structured framework. These limiting factors are a particular constraint for novice designers and result in less effective ideation performance. Based on the aforementioned findings, requirements for the ideation method for novice designers become apparent. Namely, 1) a systematic ideation process from design brief to concept solution generation, 2) stimulation through a greater quantity and variety resources, and 3) a designer-friendly method. These requirements are addressed in the ideation method prototype in the following chapter.

Chapter 3 - Research Methodology and Evaluation

This chapter introduces the overall development process and an overview of the ideation method proposed in this research. Beginning by providing the Design Research Methodology (DRM) as a basis of the development process model in Section 3.1, it moves to a detailed explanation of the development process and structure, and how it corresponds to the requirements of novice designers based on the design theories and empirical research in Section 3.2. The experiment design involving data collection and its analysis are also explained in detail. Section 3.3 describes the preliminary experiments design and analysis of results to verify limitations and requirements discussed in Chapter 1 in order to establish the concept of an ideation method in the thesis. This chapter closes by providing a summary in Section 3.4.

3.1 Design Research Methodology (DRM)

Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009) was used as a framework for the development of an ideation method along with a systematic process to apply ideation theories and findings from empirical research into a developmental process and solution. DRM suggests four flexible stages in order to enhance implementation of results within academic areas and research in practical ways: Research Clarification, Descriptive Study, and Descriptive Study II (Figure 3.1).

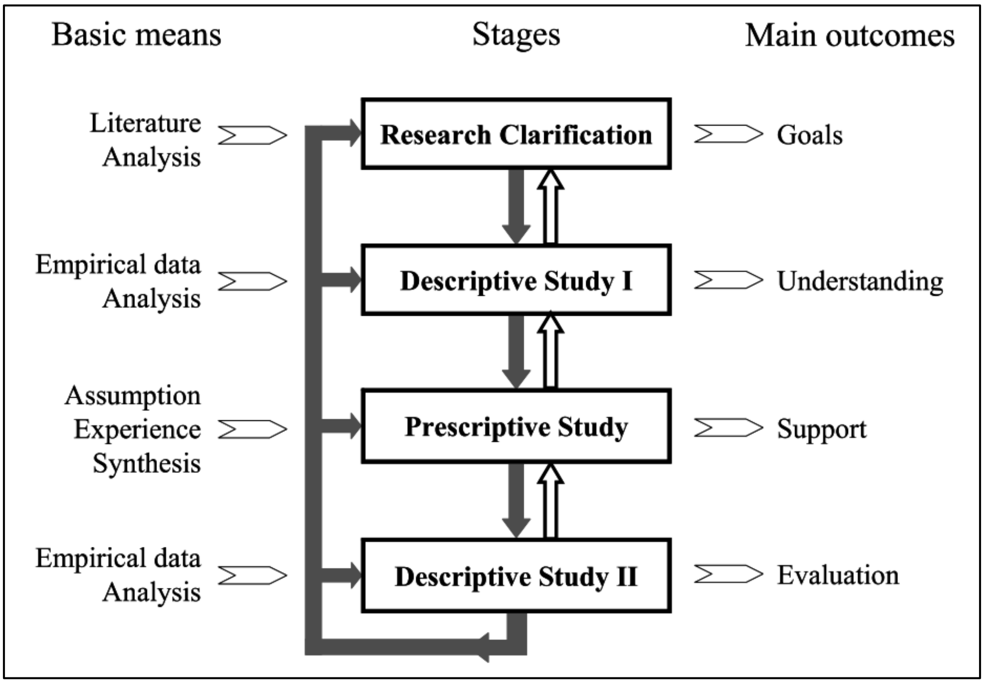


Figure 3.1 DRM framework. Source from Blessing and Chakrabarti (2009)

3.1.1 Four stages of DRM

The four stages of DRM provide development framework based on the three key issues and their iterative examination; existing and desired situation, and important facts that enable support to reach desired situation.

1. Research Clarification, the first stage of DRM, clarifies the overall research goals by describing existing and desired situations, relevant factor/s to reach the desired situation, and measurement criteria, through analysis of literature review and/or exploratory study.
2. These identified research goals are developed with the aim of understanding the certain and detailed research goals for real implementation with respect to definition of important and/or potential facts to successfully support reaching the desired situation in Descriptive Study I. The analysis of empirical data methods are commonly used to clarify the detailed context of existing problems and their types.
3. In the Prescriptive Study, the effective solution is discussed based on identified contexts along with research goals and assessment criteria through scenario, assumption, and experience, in order to design appropriate solutions.
4. Following that in Descriptive Study II, the developed solution (in the Prescriptive Study) is evaluated according to comparison with research goals (in Descriptive Study I) and assessment criteria (in Research Clarification) through empirical study. For instance, how effective the developed solution and considered fact/s to reach a desired situation can be described, and therefore provided to give insight or promote usage of research data with other researchers.

These four stages of DRM are linked by a parallel and flexible relationship, and researchers can move and iterate to another stage according to requirements. This property supports the increase in researchers' understanding and a more efficient process, compared to the rigid and linear process that causes negative impacts on the quality of results.

3.1.2 Types of DRM

It is noteworthy that the stages researcher(s) have completed and how through they have completed the steps is closely linked to the success of research and quality of the solution. According to this fact, seven types of DRM are possibly available depending on the completed stage(s), depth of undertaken study (review-based study, comprehensive study, or initial), and iteration, as described in Figure 3.2 (Blessing and Chakrabarti, 2009). Types 1 to 4 are suitable to concentrate on one particular stage. Types 5 and 6 are the ideal process as it completes all four stages with comprehensive work in two stages, however most research is conducted as Type 2 or 3 because of underestimating time and resources. Type 7 is suitable for a research group as it needs abundant resources and manpower compared to the other types.

Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based →	Comprehensive		
2. Review-based →	Comprehensive →	Initial	
3. Review-based →	Review-based →	Comprehensive →	Initial
4. Review-based →	Review-based →	Review-based → Initial/ Comprehensive ←	Comprehensive
5. Review-based →	Comprehensive →	Comprehensive →	Initial
6. Review-based →	Review-based →	Comprehensive →	Comprehensive
7. Review-based →	Comprehensive →	Comprehensive →	Comprehensive

Figure 3.2 Types of design research projects and their main focus. Source from Blessing and Chakrabarti (2009)

3.1.3 The use of DRM type 5 in this research

This research was undertaken using DRM type 5 as the most applicable development process; Research Clarification, Comprehensive and in-depth analysis of Descriptive Study I and the Prescriptive Study, and assessment of the developed solution by empirical study to provide information for the use of other researchers in Descriptive Study II.

In Research Clarification, the literature review was conducted to clarify research goals; identification of the existing and desired ideation environment of novice designers, and relevant important factors which are required by the ideation method for novice designers. In detail, academic research about designers' thought process, design theories or ideation methods that provide more efficient strategies, empirical research in ideation, and assessment criteria are analysed in order to understand the difficulties novice designers face during ideation and clarify the desired situation and important facts to reach.

These research goals were clarified and detailed in order to understand the specific research goals and factors to develop the ideation method in Descriptive Study I. The empirical data about comparative analysis of ideation activities and performance between novice and expert designers and important requirements for the ideation method were reviewed, with respect to identifying the requirements for an ideation method to resolve the ideation limitation of novice designers (Ho, 2001; Kavakli and Gero, 2002; Ball et al., 2004; Hey et al., 2008; Dinar et al., 2015; Self et al., 2016). In conclusion, a comprehensive ideation process which consists of specified appropriate strategies was identified as a major requirement for the ideation method if novice designers are to perform efficiently as experts.

In the Prescriptive Study stage, the previous identified context about the research goals was drawn together into the development of an ideation method as solution. This process was iterated to test and evaluate the developed methods according to a desired situation and assessment criteria by scenario works, assumption, and individual experience. The ease and intuitive use of the method developed, one of the significant desired factors (Shah et al., 2000), became the basis of the ideation method concept as solution with the aim of supporting the usage of practising novice designer(s) in actual fields. This basis was clarified to the specific solution concept; the method to form a comprehensive ideation process based on revision and combining of general ideation methods. The identified facts in Descriptive Study I were specified according to the identified solution concept and three stage ‘ideation process model based on designers’ thought process’ along with development of initial method structure. As a result, the following concepts arose, reviewing sources to generate appropriate analogies in response to the design brief (obtaining fundamental knowledge from suitable sources and their style and stimulation through a greater quantity and variety of resources) (Nonaka et al., 2000; Laing and Masoodian, 2016; Goucher-Lambert and Cagan, 2017) and systematic idea generation process (for increasing the number and diversity of ideas, and decreasing fixations) (Kavakli and Gero, 2002; Shah, 2003; Dinar et al., 2015; Vasconcelos et al., 2017). The aforementioned contexts drove the ideation method process; review, select and develop general ideation methods with respect to how far they satisfy given requirements (within three stages of the aforementioned ideation process and the enhanced links with other stages) through iterative scenario models and empirical research. As a result, an ideation method which consists of a variation version of three general ideation methods (database, perceptual mapping, and brainstorming) was developed as a solution. The information relating to Research Clarification and Descriptive Study I are described in Chapter 1 and 2, and the contexts of the Prescriptive Study and Descriptive Study II are provided within Chapters 3 to 7.

In summary, DRM type 5 provided a noteworthy systematic development process for application of academic knowledge (literature review, empirical research data, design theories, and ideation methods) into a practical method (ideation method for novice designers). In particular, the large volume of academic resources could be specifically selected and reviewed, and linked with related themes along with the ideation method development process. Obtained knowledge from the comprehensive and in-depth literature review in Descriptive Study I was directly linked to the solution development process in the Prescriptive Study. Descriptive Study II, the empirical study for assessment of the developed ideation method, provided the detailed evaluation data and further discussions according to research goals and assessment criteria.

3.2 Research design

The priority for the research after Descriptive Study I was the development and assessment of KEDIM with respect to the research goals that were identified in Research Clarification (Blessing and Chakrabarti, 2009). In this research the following high priority requirements were identified as important for an ideation method to improve the effectiveness of the ideation performance of novice designers: 1) a systematic ideation process from design brief to concept solution generation and 2) stimulation through a greater quantity and variety of resources, with 3) a designer-friendly method.

In response to these requirements, the focus of the research design was subsequently directed to a combination of quantitative and qualitative research methods. Figure 3.3 provides a structural overview of the research design. As the first stage of DRM, Research Clarification was explained with research goals based on limitations of ideation methods for novice designers. After this, the empirical research background and results that identify important limitations and build the solution concept are given as Descriptive Study I in Section 3.3. The obtained data and research goals are drawn to the development of the Knowledge-Enabled Ideation Method (KEDIM) that provides systematic ideation stages which is the Prescriptive Study. The first, second, and third stages of KEDIM are presented followed by background and detailed explanation in response to the research goals and literature review in Chapter 4 and 5. It also reports how design cases were collected and populated to the database. Finally, Chapter 6 reports the evaluation of KEDIM including an outline of experiments, collected data, and its analysis in response to the research goals as Descriptive Study II.

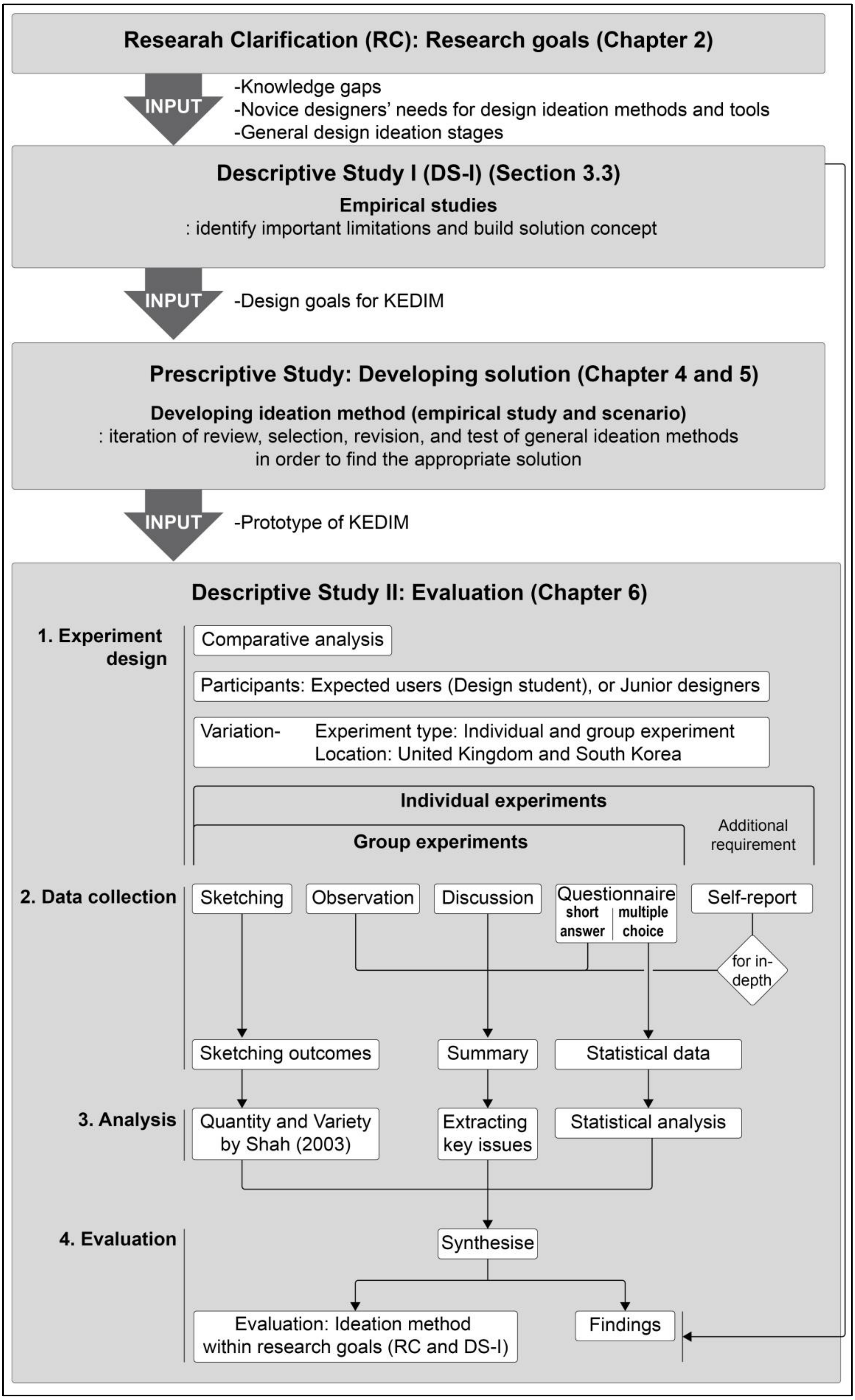


Figure 3.3 Research design structure

DRM type 5 was used as a basis to build the structure of the research concept, which meant undertaking comprehensive solution development and assessments of the Prescriptive Study and Descriptive Study II based on a combination of quantitative and qualitative research. Quantitative research explores a mass of data to identify arising or specific issues within design theories or research, for instance statistics, experiments, observation and closed questionnaires (Blessing and Chakrabarti, 2009). Qualitative research provides a solution development process based on increasing researchers' understanding of complex facts through empirical research (Orthel and Day, 2016). It refers to an analytic induction process; data collection, formulation of data, and testing. For data collection, open-ended results are used such as interviews or observation, and researchers sequentially write detailed descriptions for appropriate interpretations and understanding (Blessing and Chakrabarti, 2009). The obtained data sometimes shows unexpected results, and increases the validity of experiment design (Dinar et al., 2015).

In this research, quantitative research was mainly used for generation of important facts from various redefined facts along with solution development stages: identification of resarch goals and facts for the initial stage of the solution development process, and design of empirical research (phase 1 in solution development in Figure 3.3 Research design structure). On the other hand, qualitative research specifically focused on the solution development process in the Prescriptive Study. Firstly, iterative solution development was undertaken with the aim of aiding sophisticated and detailed application of facts into solution. Secondly, evaluation experiments were designed to obtain diverse data for providing rich description as in-depth assessment. For the design of evaluation experiments, a combination of quantity and quality research was used to obtain various data which is related to the effectiveness of the solution in response to the research goals and facts.

In summary, research methodology, DRM type 5 using a combination of quantity and quality research focused on an iterative solution development process with redefinition of quantitative facts: empirical research, high number of design cases with general method, and a clarified solution concept with respect to design detail and sophisticated solution results. In particular, the design of evaluation experiments involved quantitative and qualitative data for in-depth understanding and assessment. The detailed contexts of the solution development process in the Prescriptive Study and the evaluation experiment's design in Descriptive Study II are provided in following sections.

3.2.1 Developing solution in the Prescriptive Study

The Prescriptive Study aims to design a solution development method in response to the research goals and facts in the previous Descriptive Study I. Identification of facts from empirical research supports understanding of specific facts and their correlation within a comprehensive situation of research goals along with development of sophisticated solutions. In particular, the Prescriptive Study based on qualitative research focused on implementation of an effective solution (ideation method for novice designers) based on redefined core solutions which were identified by comprehensive and in-depth understanding of identified research goals and relevant facts. These concepts drove the structure of the solution development process which is separated into two parts, phase 1 to clarify solution concepts from various facts in literature, and phase 2 for the solution development process (the Prescriptive Study in Figure 3.3).

In phase 1 of the solution development stage, empirical research was undertaken to examine identified facts in literature in respect of the designers' perspective in order to draw a solution concept. In general empirical research (Valkenburg and Dorst, 1998; Self et al., 2016; Laing and Masoodian, 2016), the way of identifying findings progresses with observation of participants by researchers. On the other hand, in this research, the researcher directly joined as a participant in the empirical study; generation of perceptual mapping including solution facts sourced in literatures (Goldschmidt and Smolkov, 2006; Chuang and Chen, 2008; Laing and Masoodian, 2015; Laing and Masoodian, 2016) with usage of general tools. The obtained data (in perspective of designers) led to focussing on specific facts through grading (important, less important, and not relevant facts).

Phase 2 then focused on the development process of a sophisticated and detailed solution based on the solution concept in phase 1. Overall, the process of solution development evolved by focussing on two themes (solution facts in literature, and the method for application), their matching, and revision, as described below.

- Stage 1. With respect to each of the three stages of the ideation process model (Figure 2.5), redefined solution facts within various areas and general ideation methods were examined respectively, then the results in the two groups were matched and developed based on scenario.
- Stage 2. Each variation version of the general method was selected with respect to the appropriateness of each of the three stages with required facts and enhanced links with other parts.

Iterations of the development process increase the researchers' understanding of facts and the completeness of the solution, especially when findings in literature are applied in practical ways (Nonaka et al., 2000; Blessing and Chakrabarti, 2009; Cash, 2018). Therefore, stage 1 and 2 were repeatedly conducted in order to apply facts into the method in appropriate ways, along with cyclical reviewing of facts, redefinition of facts, revision of the method with redefined facts, and evaluation. In summary, Prescriptive Study based on qualitative research using empirical research and an iterative development cycle led to investigation of a sophisticated solution with respective application of empirical literature data in response to research goals.

3.2.2 Evaluation experiments in Descriptive Study II

According to DRM type 5, the defined solution result in the Prescriptive Study needs to be evaluated according to the assessment criteria (in Research Clarification) and research goals (in Descriptive Study I) in Descriptive Study II with respect to how far the developed solutions and selected fact/s are effective in the desired situation and what they contribute to the discussion for further investigation.

In the design field, evaluation experiments are generally advanced for comparative analysis (Valkenburg and Dorst, 1998) and observation (Chuang and Chen, 2008) based on four stages; experiment design, data collection, analysis, and evaluation (El-Zanfaly, 2015; Laing and Masoodian, 2016). Design of variations (control and independent variations) is a core part of experiment design to obtain appropriate data pertaining to facts for exploration or evaluation according to the researchers' intention. The obtained data (from specific outcomes, questionnaire, discussion, observation, or others) is then interpreted to gain evaluation data (rich description, statistical results or others) with regards to research goals. The evaluation data specifically focuses on providing evidence for the efficacy of their research, however the usage of research data with other researchers also needs to be regarded as being an important issue (Blessing and Chakrabarti, 2009).

In this research, the evaluation experiments mainly focused on obtaining varied and rich data from empirical experiments in response to the research goals, based on a combination of quantitative and qualitative research. It was also followed by the four general stages of experiment design, data collection, analysis, and evaluation. The detailed information of the four stages will be provided in the following Sections 3.2.3 to 3.2.6.

The design of the evaluation experiments and relevant issues (participant consent, materials, data protection and others) for ethical and political considerations were established through discussion with the ethical committee of the University of Leeds, and approved in advance (Reference number: MEEC 17-003 and MEEC 17-026).

3.2.3 Experiment Design (first stage of evaluation experiments)

Experiment design, which is the first stage of Descriptive Study II, builds the experiment structure in order to obtain data for evaluation of the investigated solution in the Prescriptive Study (see Descriptive Study in Figure 3.3). Results of obtained data mainly need to provide rich, detailed and clear information, to demonstrate evidence of the efficacy of the solution developed in response to research goals, as well as to promote usage by other researchers. In this research, experiment design focused on empirical workshops that expected users to directly use the solution developed and obtain varied data during the workshops.

Prior to explaining the experiment design, it is worthwhile introducing the scope of the experiments (location and participant groups) in order to obtain both varied and general data whilst mitigating bias and considering unique environmental properties:

- Location: research about ideation and novice designers has been concurrently conducted around world. Evaluation in each specific country has possibilities to show different results, according to different variations (unique cultural influence or educational curricula according to location). Therefore, using multiple locations for the experiments was important to obtain meaningful evaluation information.
- Experimental groups: designers conduct ideation in diverse situations according to the number of designers and environment. Regarding experiment analysis research, this research was designed for two groups, small group work (around 5 designers) and individual work in a private environment.

For group work, with respect to limited time and participants' ethical issues, the experiment process focused on the part of solution (Systematic Brainstorming (SBI)), which is directly related to ideation, and other parts (Database of Design Cases (DOS), and Perceptual Mapping Generation Software (PMGS)) were optionally provided to participants according to the given situation and participants' condition (see Table 3.1, Table 3.2, and Table 3.3). In addition, the detailed context of SBI, DOS, and PMGS is explained in Chapter 4Chapter 1. This experiment was designed based on a combination of quantitative and qualitative research, with the aim of obtaining rich and comparative data (general and specific issues) from the process and outcomes of workshops with a five piece data format including quantitative and qualitative research: sketching outcomes, questionnaire, self-report, observation, and discussion (see 3.2.4 for detailed context).

Table 3.1 Outline of experiments

Location: United Kingdom and South Korea Participants: Novice (student) designers						
	Experiment 1 (Group work)			**Experiment 2 (Individual work)**		
	Workshop	**Observation**	**Discussion**	**Questionnaire**	←	**Self-report**
DOS	◐	◐	◐	◐	◐	◐
PMGS	◐	◐	◐	◐	◐	◐
SBI	●	●	●	●	●	●
● Compulsory / ◐ Option / - Not concerned						

Table 3.2 Plan for group work experiment

Step	**Time (minutes)**	**Action list**
1. Introduction	20	- Research and experiment background - Complete ethical review and security maintenance - Explain the brainstorming method
2. Ideation	60	(Option) Undertaken DOS and PMGS in the group working. 1.Firstly, participants review the populated database in text format - book style (540 cases including 1750 data). The database result is explained in Chapter 4. 2. Secondly, participants used the perceptual mapping software based on database file (the same version reviewed in the first stage) in group.
	60	Undertake brainstorming design ideation with two groups for comparative analysis 1. Experimental group: SBI 2. Control group: unstructured (blank paper)
	Researcher conducted observation and discussion with participants who made interesting or distinguished actions, asked to talk, or faced difficulties, or those selected at the researcher's discretion according to situation.	
3. Evaluation	20	Questionnaire to evaluate the method used and obtain feedback
4. Closing remarks	5	-

Table 3.3 Experiment design for group work experiment for SBI

Variables		Control group	Experimental group
Control Variable	Participants background (age, education, environment)	Same degree course and year of study	
	Experiment design (materials, topic, time plan)	Identical	
Independent Variable	Brainstorming format	Unstructured	SBI

3.2.4 Data collection (second stage of evaluation experiments)

The data collection stage was designed for obtaining suitably rich data for evaluation of the solution and was developed with the following in mind; the kinds of data format that are required, and how to collect them during evaluation experiments. The collected data was used for evaluation over the next analysis stages. As previously stated, the design of evaluation experiments aimed to collect appropriate data within empirical workshops that expected users to directly use the solution developed. Five data types were collected from the experiments; sketching outcomes, questionnaire, self-report, observation, and discussion, and Table 3.4 describes in detail the context. The five sets of data provide more comprehensive data for analysis compared to general evaluation experiments which commonly collect fewer than three data types.

This five data format includes a mass of information that needs to be appropriately reorganised to gather and format suitable data as well as increasing the researcher's understanding at the next Analysis stage. The five data format results were reorganised into three types with respect to the types of raw data: sketching outcomes, summary, and statistical data.

- Firstly, sketching outcomes are the unique data that experimental and control groups ideated with developed and general methods for comparative analysis. These outcomes also include a wealth of information which can be analysed by quantity and variety using Shah's metrics (Shah, 2003) and detected by qualitative research. Therefore, sketching outcomes were separately handled.

- Secondly, summarising was used to gather textual information such as notes and description from observation, discussion, short answers of questionnaire, and self-reports.

- Thirdly, statistical data was obtained from multiple choice questions in questionnaires including the evaluation of part of the solution and individual ideation background.

The reorganised three data types were also classified according to variables of experiments; location (the United Kingdom and South Korea) and experiment groups (group and individual work).

Table 3.4 Five data type from evaluation experiments

	Data type	Description
1	**Sketching outcomes by participants**	During experiments, brainstorming will be mainly used for ideation according to given theme. For comparative analysis, experimental and control groups used the developed and general method respectively.
2	**Questionnaire by participants**	At the end of experiments, participants provided data about evaluation of method used and individual ideation background through the questionnaire which consists of short-answer and multiple choice questions. For this, online survey was preferred, however it was replaced with paper output style in case there was not enough computers.
3	**Self-report by participants**	It will only be required for individual participants, not for group work. The participants used the methods at their convenience in a location of their choice (e.g. home). And this method is suitable to obtain rich description from them (Jonson, 2005). Participants will write feedback in an uncontrolled environment.
4	**Observation by researcher**	Observation during work allows for the identification of issues and participants' overall process (Chuang and Chen, 2008; El-Zanfaly, 2015; Laing and Masoodian, 2016). In this research, the researcher directly observed participants for group work, and used video recording in individual work sessions.
5	**Discussion between researcher and participants**	Discussion can obtain open-ended information from participants. For this research, the researcher directly made conversation according to observation (general, common and unusual actions).

3.2.5 Analysis (third stage of evaluation experiments)

The analysis stage involved detailed examination of the collected data in order to measure the effectiveness of the solution investigated and understand in detail issues from participants during experiments. In this research, the three types of data obtained (sketching outcomes, summary, and statistical data) were respectively analysed through appropriate methods.

Firstly, each of the sketching outcomes were assessed by number and variety of ideas generated according to Shah's assessment metrics (2003). In Shah's metrics involving four criteria (quantity, quality, variety, and novelty), ideation focuses on quantity and variety of solutions being naturally driven forward to the generation of quality and novel solutions as the ideal outcome (Hernandez et al., 2010). In Research Clarification and Descriptive Study I, quantity and variety were primarily used with the aim of focusing on specific solution concepts and gathering specific relevant literatures. Therefore, each sketching outcome was analysed on the quantity and variety of Shah's metrics (2003). Moreover, they were also scrutinised in respect to where ideas came from, how they developed, their correlation with other ideas, along with comparison between the experiment and control groups.

Secondly, summarised data from textual information (observation, discussion, short answer of questionnaire, and self-report) were analysed with scrutiny in order to extract key issues. Key issues focused on open-ended description data relating to common, unusual and specific activities of participants. It also sought to obtain pros and cons, and further revisions for solutions developed by participants. Evaluation by self-reporting and short answer questions served to understand gaps between the intended objectives of the solution and actual functions for further revisions and feedback. Observation data by notes (group work experiments) or video recording (individual experiments) was examined with respect to participants' unconscious activities and performance in line with identification of difficulties, ideation process, and opportunities from the solution developed. These identified issues from the comprehensive information obtained were classified according to similar properties and groups, in order to extract key issues regarding general and unusual activities of participants.

Thirdly, statistical analysis was used to understand data from multiple choice questionnaire questions as closed-end information. This evaluation data well reflected the ease of use and the effectiveness of the solution developed, and participants' individual ideation background.

The analysis of the three data formats was reviewed according to the location of the experiments (the United Kingdom and South Korea) and the experimental group (group and individual work) along with comparative analysis between experimental and control groups to obtain the evidence and further revisions of the solution developed and provide data to other researchers. The experiments' results are provided in Chapter 6.

3.2.6 Evaluation (fourth stage of evaluation experiments)

Evaluation, the final stage of Descriptive Study II, measures the solution developed based on analysis of data according to research goals in Research Clarification. Measurement means the effectiveness of the solution, but also refers to comprehensive descriptions. In this research, the evaluation stage comprehensively assessed three types of analysis data for comparative analysis from two perspectives; the solution developed and the background of the solution.

Firstly, the solution developed was assessed based on multiple analysis data. The ease of use and effectiveness of the solution developed were assessed through sketching outcomes, extracting key issues from summary, and statistical analysis. In particular, sketching outcomes reflected the direct evaluation data of part of the solution (variation version of brainstorming) in quantity and variety of ideas (Shah, 2003), and correlation of ideas generated. Participants' activities in the workshop were also evaluated through description with respect to general, unusual, specific, and unexpected issues.

To provide an extended version of solution analysis, used facts from literature were assessed along with a comparison of the expected benefits and actual effectiveness in the practice method. This assessment data was applied to the evaluation of DRM type 5, as used design methodology for the overall solution development, with respect to how far it systematically supports the identification of research goals and facts in literature, and develops solutions and evaluation.

3.2.7 Biologically inspired design

In the solution development process in the Prescriptive Study, specific theme(s) can be used based on individual assumption and experience (Blessing and Chakrabarti, 2009), because it enables to efficiently build new guidelines focusing on the solution concept, and it can be developed further for more general usage.

In this research, a biologically inspired design theme was used as the resource for testing and evaluating empirical studies; phase 1 empirical research and phase 2 development solution. Biologically inspired design refers to design form outcomes that are influenced by resources from Nature in a diverse way at the design ideation stage (Fu et al., 2014). This design theme contains rich design case information (the number, kinds, and various ideation strategies) along with history from the industrial revolution, Art Nouveau, Art Deco, Organic design, and organicism, as described in Figure 3.4

(Alberto, 2010). In particular, their forms include the ideation process from motifs to final outcomes (Wilson et al., 2010). In this research, these properties of biologically inspired design themes support solution development and evaluation.

For instance, empirical research (phase 1 within the Prescriptive Study in Figure 3.3) for generating perceptual mapping includes five times more cases compared to the general results, in response to the identified important facts, and supports generation of appropriate analogies through stimulation from quantitative design case information including colour images. Using design cases from a common origin (motifs) enabled focussing on the concept of solution with specific guidelines, rather than the use of randomly selected design cases.

For the evaluation of part of the solution investigated (variation version of brainstorming), collected outcomes from participants were easily analysed along with tracking of the development process and correlation of ideas generated, because the property of biologically inspired design includes the ideation process from motif to outcome (Wilson et al., 2010). In this light, the symptoms (misapplied analogy and improper analogical transfer) which are caused by an insufficient degree of working at each ideation stage and an illogical process (Feng et al., 2014) were clearly observed. Properties of biologically inspired design themes include rich data production and reflecting the ideation process effectively which supports the development of detailed solution concepts and the analysis of collected data from participants. Solutions applied in this research and results were based on biologically inspired design, and these solutions and results enable the move forward to more general usage.

Figure 3.4 Examples of biologically inspired design (examples from list of Alberto (2010)).

3.3 Database and perceptual mapping software process design

To achieve the research goal of enhancing the linkage of application of findings in academia into practise methods, the solution development process was implemented with two phases; empirical research for verifying how far methods for practising designers can correspond to facts in the academic area in phase 1, and solution establishment based on findings in the previous stage in phase 2 (Figure 3.3). This section provides detailed information of empirical research in Prescriptive Study 1, along with background, process, outcomes, and findings, with the aim of designing a solution concept and development in phase 2. In addition, the context of Prescriptive Study phase 2 will be given from Section 4.1.

In phase 1 of the development solution, empirical research and analysis was implemented along with how far key facts in literature can be applied to the ideation method with the aim of establishing a solution concept in phase 2. As a key fact, use of a high number of relevant pieces of information and colour images promotes generation of assumption, clues, and others within creative ideation with increased stimulation, and was thus selected on this basis. It is a clear and simple concept in academic as well as practical fields, so findings of empirical research could review the linkage between the two areas. Therefore, it was a suitable research theme to explore the linkage and application between the two areas.

The aforementioned contexts were drawn into the generation of perceptual mapping involving more cases compared to general outcomes. The researcher directly joined participants in order to closely review in perspective of the practising designers, compared to general research focused on observation of participants by researchers. Perception is identifying attributes from physical sensation such as sight in order to give meaning, and it follows three steps, recognition, analysis and interpretation (Solomon, 2016). The perceptual mapping method, which is synonymous with positioning mapping, is the tool for understanding, evaluating or analysing the situations or phenomenon of target area (Chuang and Chen, 2008). This normally progresses with two steps involving defining the axis first, and then placing cases according to the axis definition. From the generated results, users can learn patterns and expectations (Solomon, 2016). Due to its simplicity this method has been widely using in marketing, design, mechanics, and misc. General outcomes can be obtained using unspecialised software such as Microsoft's PowerPoint, Excel, and QSR international's NVivo 11, and this research used Adobe's Illustrator.

As a result of empirical research, perceptual mapping including 180 design cases was generated (six times more compared to general outcomes) as described in empirical research outcome in Figure 3.6. To investigate how far the perceptual mapping generated is able to be modified according to the designer's intentions an additional four variation outcomes were generated, as described in Figure 3.5. The reviewing of empirical research outcome 1 identified unexpected difficulties. Perceptual mapping can only show three types of information (case image, and their location according to axis definition), a major limitation of the ideation method in Research Clarification. When the number of cases in perceptual mapping increased 6 times (from 30 to 180), it intensified confusion along with difficulties of how it can be comprehensively understood and where the focus should be. In the making process, placing image cases according to axis definition was challenging because of difficulties to remember accurate case information depending on retrospective memory, and the requirement for a high level of concentration for comparison with related cases. These limitations were to be taken into account as requirements for revision: visualise background information of each case data according to designers' intention. As a result, a circle frame was marked on each image to refer to the design development environment, design resources and inspiration, manufacturing method, and production year. It will be called the coding system in this research. The outcome 2 and coding definition are illustrated in Figure 3.6. It was also dealt with as an important part of the solution development phase 2 in Section 4.3.2.

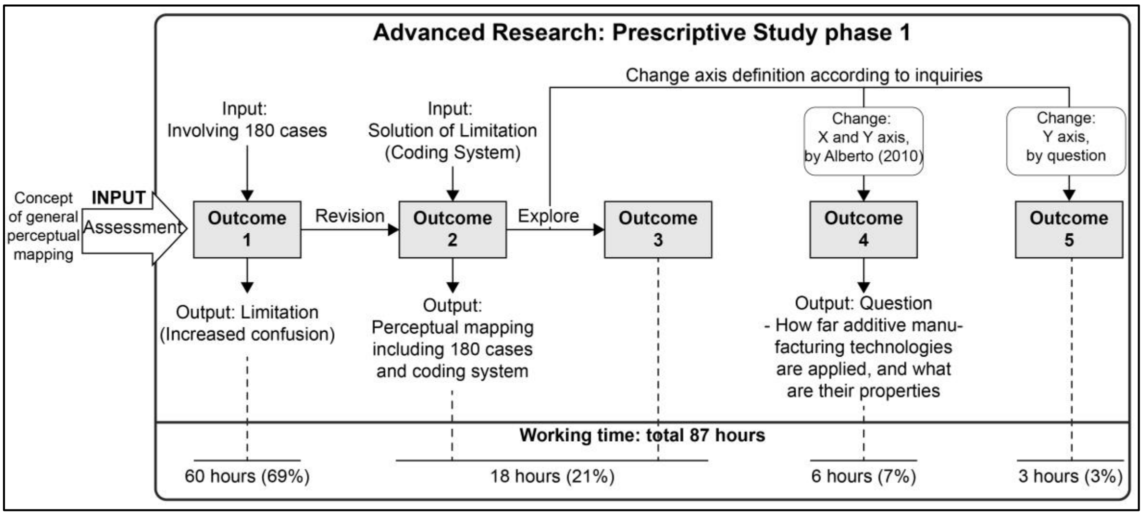


Figure 3.5 development structure of advance research outcomes

Empirical research outcome 3 in Figure 3.8 only shows coding without case images of outcome 1, to assess the coding system with respect how far supporting comprehensive reviewing of high number of design cases. The cases images involving coding system in empirical research outcome 4 (Figure 3.10 a) was replaced according to different X, and Y axis (timeline, and three types of motivations from nature) from 'design inspired by nature: from the industrial revolution to the beginning of the XXI century' by Alberto (2010) (Figure 3.10 b). This outcome raised the question, how far additive manufacturing technologies were applied into cases, and it drove the replacing of cases in outcome 2 with a different Y axis definition (scale) in Figure 3.9.

As a result of empirical study with respect to application of important facts in literature into the general ideation method, major limiting facts were identified in perspective of practise designers: unsystematic making processes and tools. Unsystematic processes and tools for generating the perceptual map were the primary limitation. 180 cases were approximately placed according to axis definition, then it precisely placed by comparison with surrounded cases, as is the usual process of general perceptual mapping. Assessment and placing of cases was undertaken simultaneously, and retrospective memory used to remind of background information of design cases, but this was identified as being insufficient due to inaccuracy and details having been partly forgotten. Therefore, information searching was undertaken simultaneously. These complex processes caused working time to increase rapidly as the number of cases went up due to the leap in considerations to be made among the design cases. In particular, it also had a negative impact on the credibility of outcomes generated, because it was observed that all or part of coding in some cases was omitted in Figure 3.7 and Figure 3.8

These limitations particularly drove the requirement for unlimited generation time in cases involving high numbers. To generate five outcomes in the empirical research took a total of 87 hours (6 hours per a day) (see working time section in Figure 3.5). Ten days (60 hours/ 69%) were used for making outcome 1 involving collecting and reviewing 180 cases. For coding system (outcome 2 and 3), three days (18 hours/ 21%) were spent re-searching accuracy of design case information. The replacing of cases according to changed definition of two axis (outcome 4) and one axis (outcome 5) took one day (6 hours/ 7%) and half a day (3 hours/ 3%) respectively. For instance, although the number of cases increases 6 times in outcome 1, the used time was dramatically increased by 30 times (Table 3.5). It also required a considerable amount of time for generation of coding systems, and replacing cases according to different axis definition. It also needs to be noted that this time consumed had little relationship with creative ideation, however, it consumed much energy and concentration. The aforementioned findings identified that the required time is the major obstacle to generating perceptual mapping involving a high number of cases and changing according to designers' inquiries within exploratory analysis.

Table 3.5 Summary result of two perceptual map generation methods

	General cases	Empirical research outcome1	Comparison
The number of cases	30	180	A is 5 times
Used time (s=seconds)	2 hours (=7,200s)	60hours (=216,000 s)	A is 30 times
Used time per case	240s	1200s	A is 5 times
Time efficiency unit	1	5	A is 5 times
The main role of user	Chart generation		

It was noted that the outcomes of empirical research involving 180 cases with coding system were suitable for drawing analogies from the reviewing process within the ideation process model based on designers' thought processes, compared to the difficulties of the making process. The outcomes, including the coding system, presented the overall situation of a high number of cases, and then the researcher could observe specific areas or facts of cases or their background information according to intention or investigation for further exploration.

For the evaluation of the coding within Perceptual Mapping Generation Software importing this database (Section 4.3.2), Cohen's kappa coefficient was used. Kappa coefficient provides precise statistical assessment of two users' agreements, because it considers both the percentage of agreement and its actual situation (Tang et al., 2015). In this sense, design researchers dealing with creative idea generation, analogy, inspiration and fixation are using this assessment measurement (Linsey et al., 2011; Linsey et al., 2012; Wiltschnig et al., 2013; Vasconcelos et al.ss, 2017). In this thesis, 13 design cases populated by two users (the author and a product designer with 6 years' experience) were analysed. For this experiment, the total number of data elements are 156 (13*12/ 12 of 14 elements per case except database id and image in Table 4.1). 13 design cases were respectively selected from 16 sections of perceptual mapping outcome 1 (Figure 3.6) except 3 sections which did not include cases as described in Figure 3.11. For selection of cases, it was important to included diverse background (form, production year, manufacturing background). Analysis results of the populated database and coding in PMGS are provided in Section 6.3.1 and 6.3.2.

The aforementioned facts from empirical studies were drawn into the solution concept: development software for perceptual mapping generation with the aim of involving a high number of cases and coding system with decreased making time. The detailed context for development from solution concept is described over the following pages.

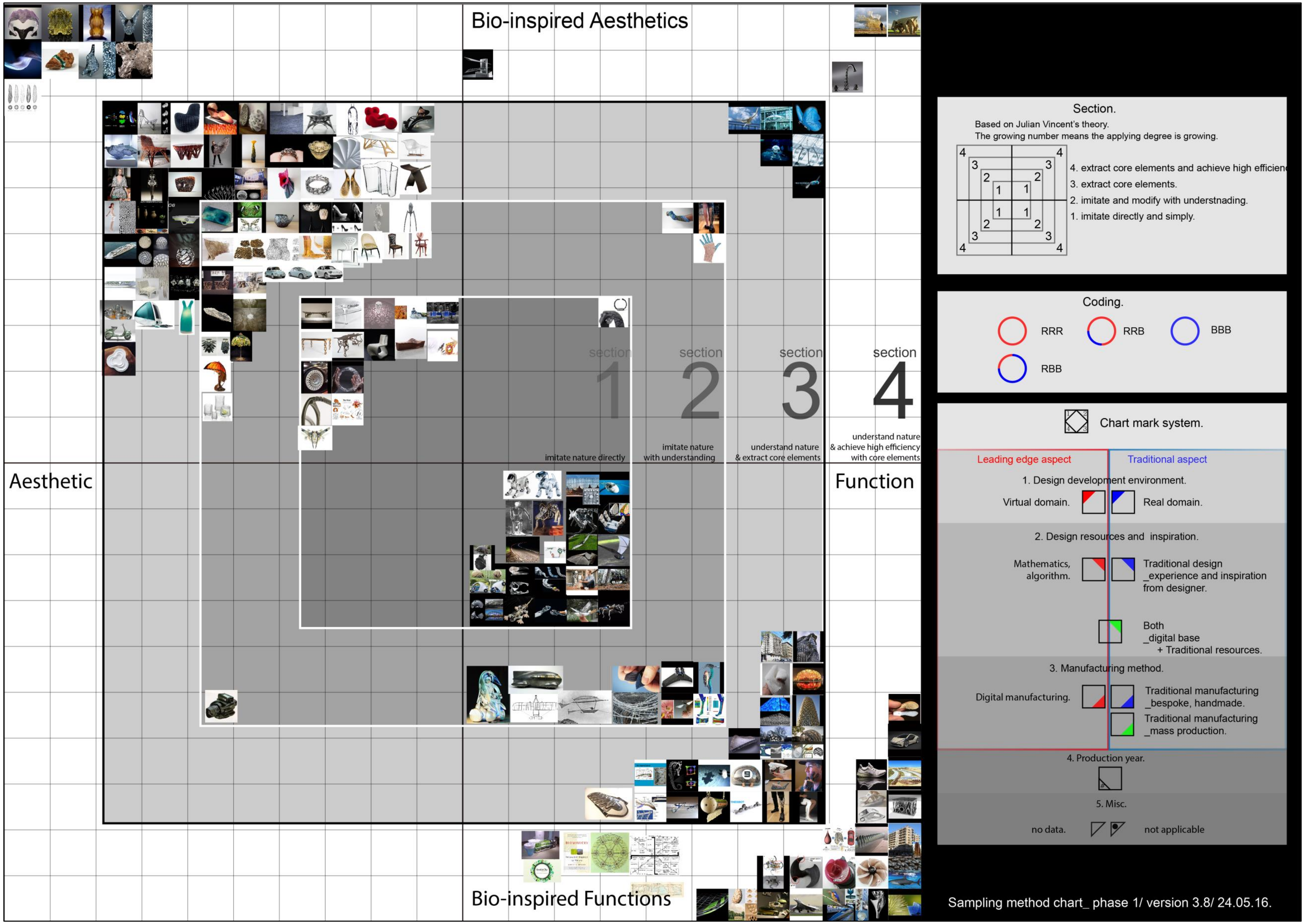


Figure 3.6 empirical research outcome 1

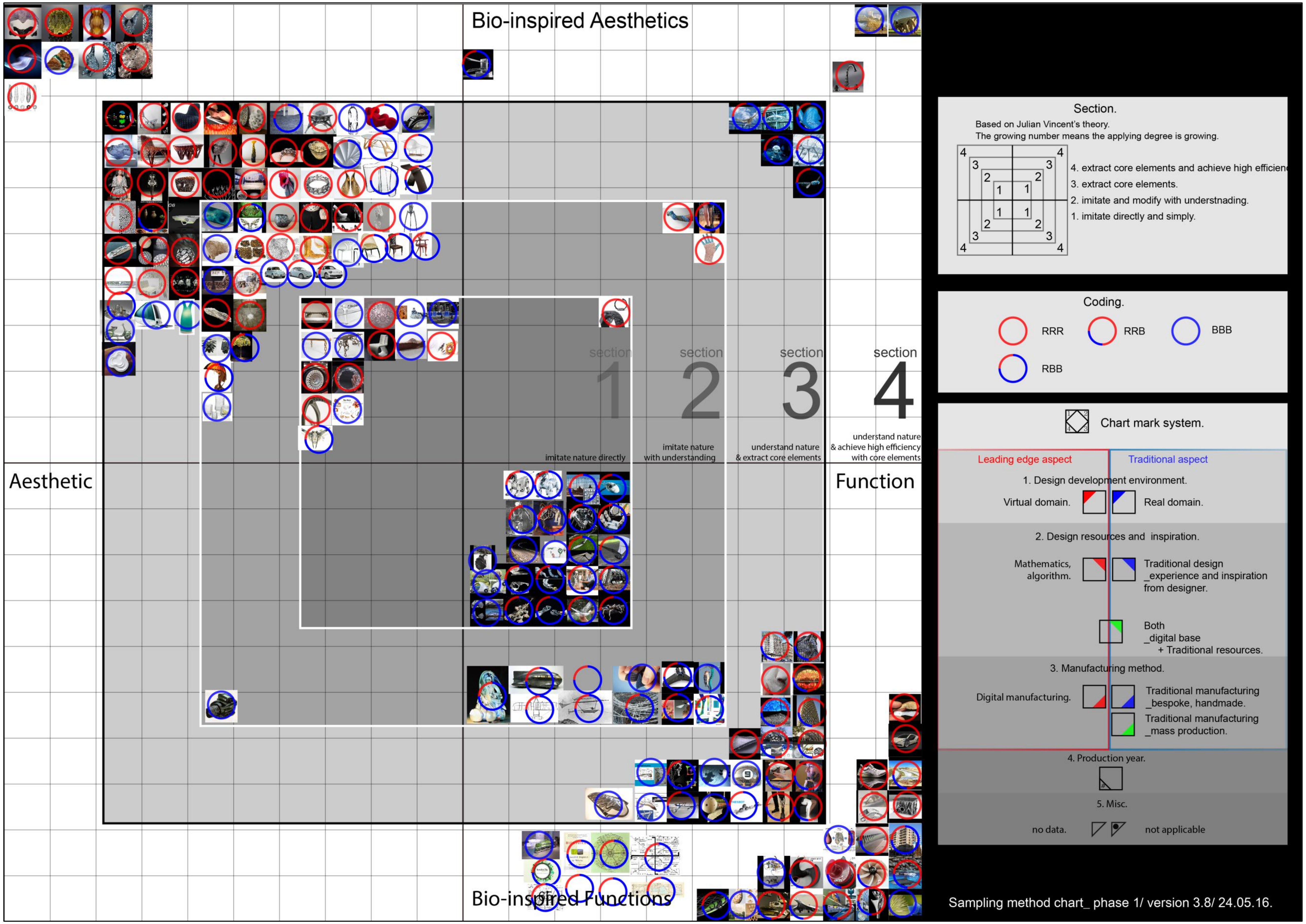


Figure 3.7 empirical research outcome 1: general type with 180 design cases with coding

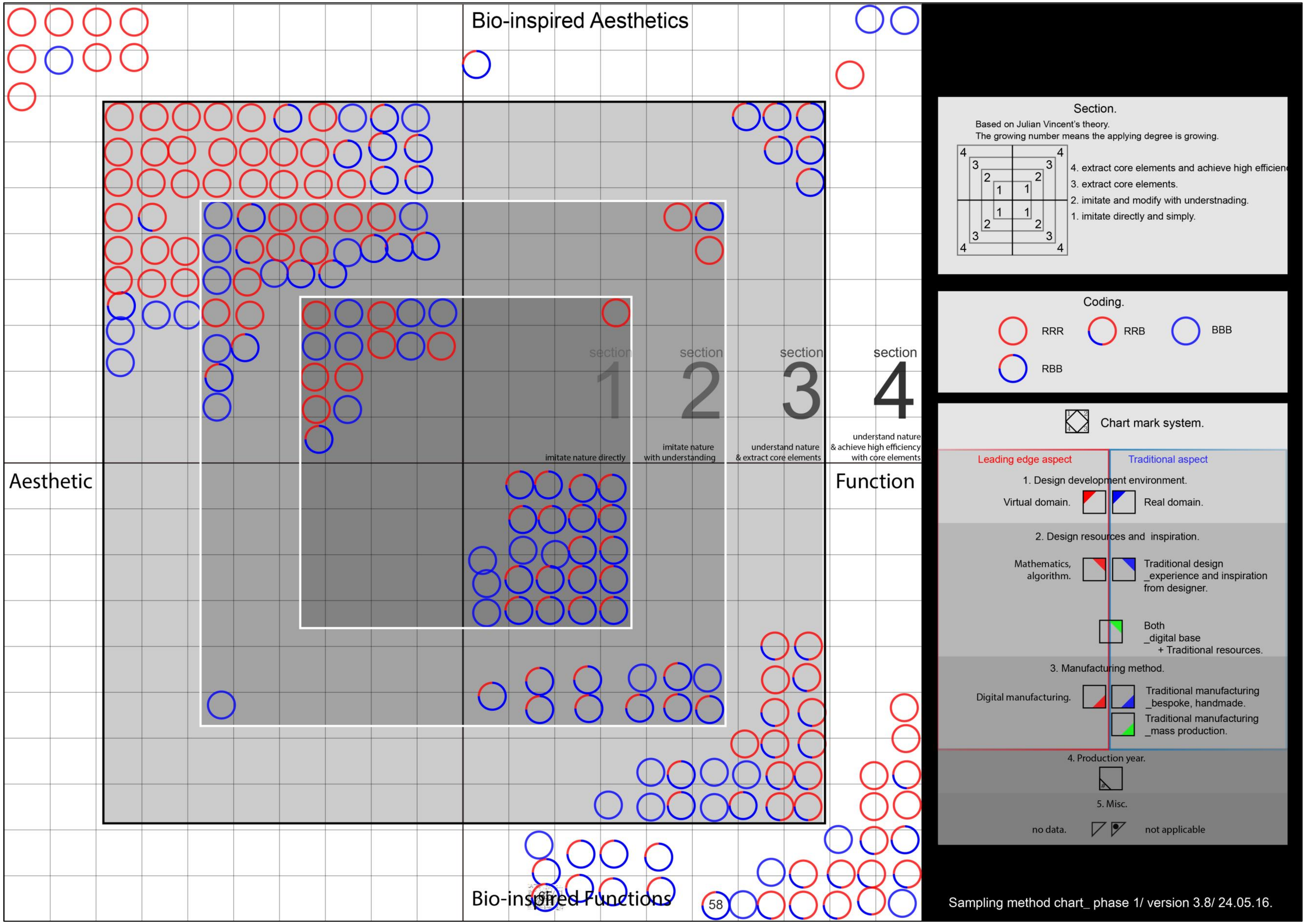


Figure 3.8 empirical research outcome 2: coding of 180 based on empirical research outcome 1

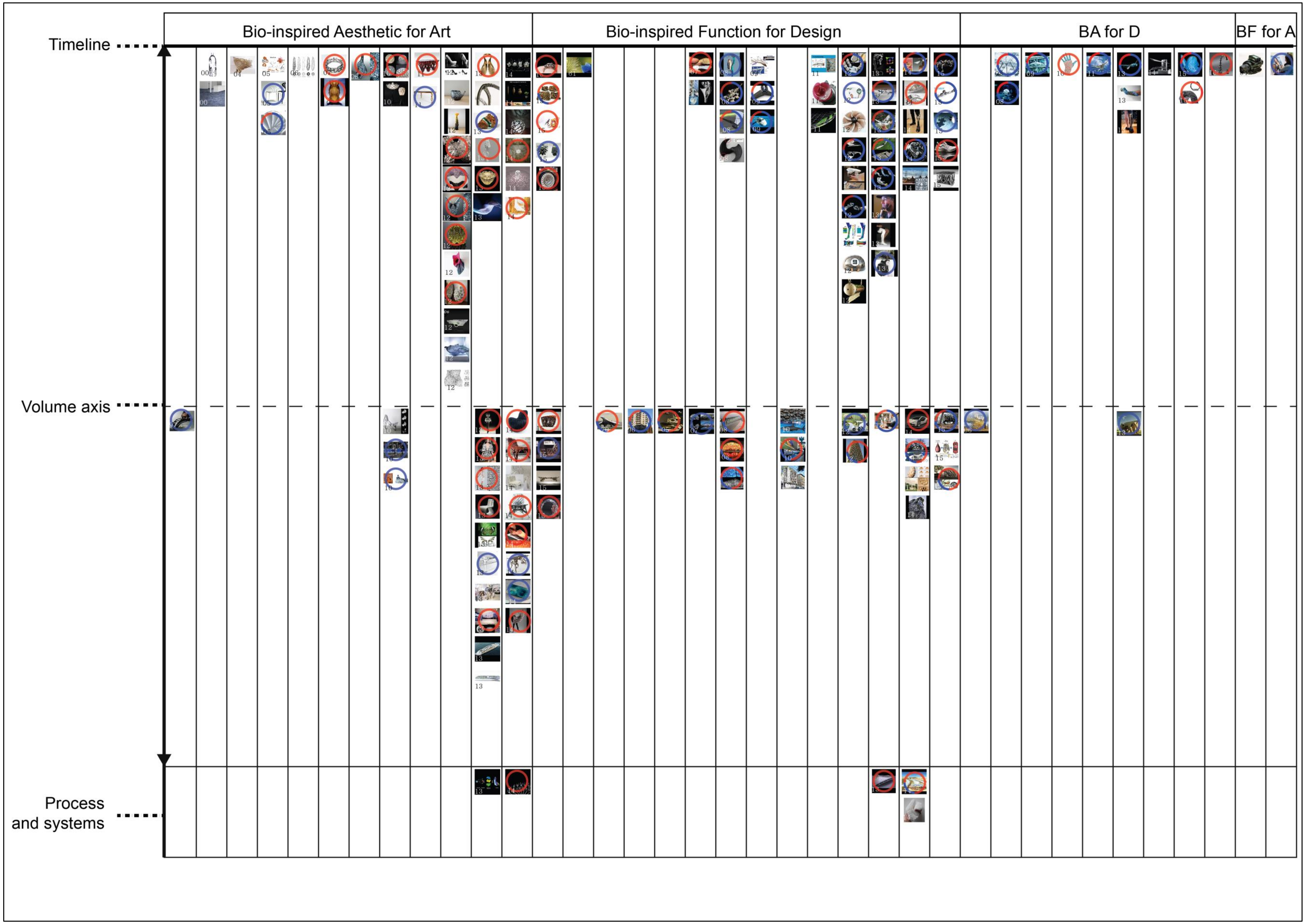
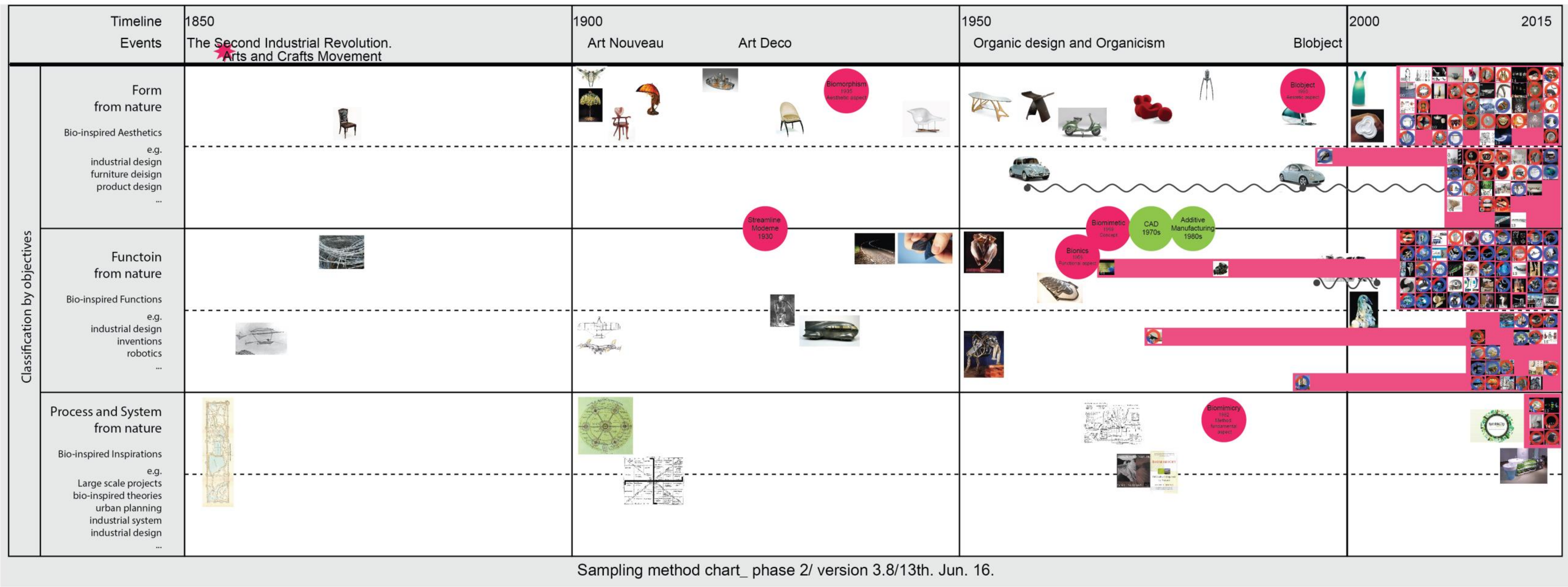
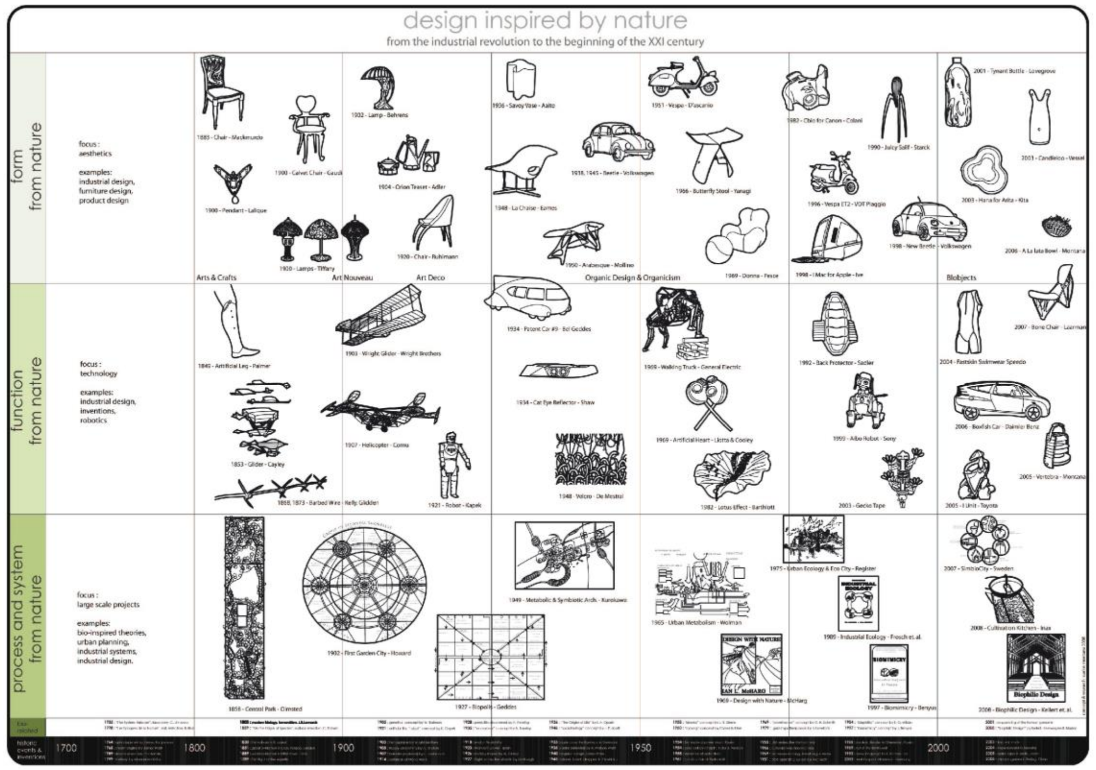


Figure 3.9 empirical research outcome 3: Exploration version of empirical research outcome 1



(a) Advanced research outcome 4



(b) design inspired by Nature (Alberto, 2010)

Figure 3.10 empirical research outcome 4 (a): redefinition of design inspired by nature (Alberto, 2010) (b)

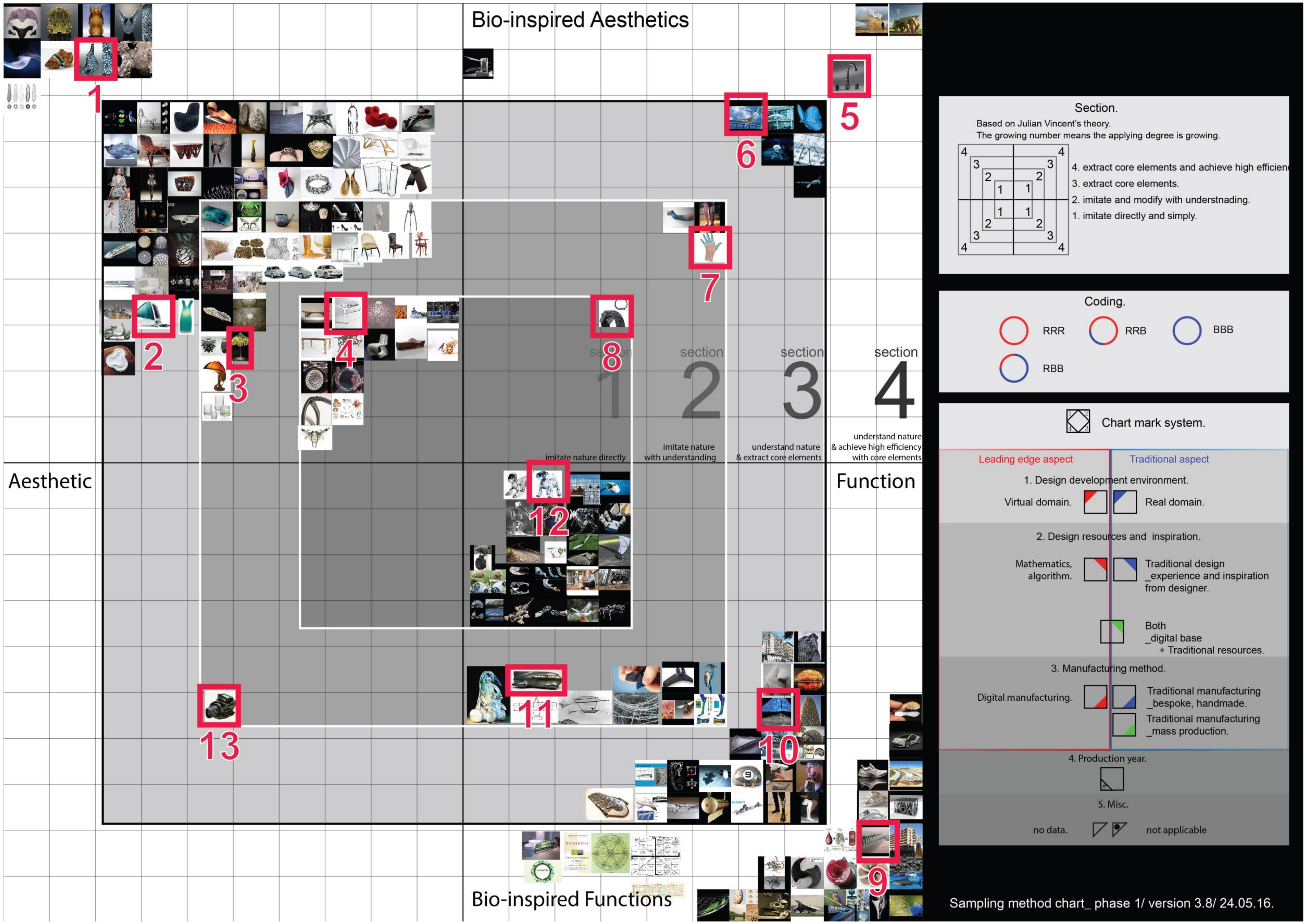


Figure 3.11 Selected cases for coding reliability test through Cohen's kappa coefficient

3.4 Summary

This chapter provides the overall framework and adopted research design followed by research methodology, research procedure, detailed description of developing solution, and evaluation according to subdivided objectives. In response to the research objectives in Chapter 1, a combination of quantitative and qualitative research was used with the aim of developing an effective solution and evaluating it.

The development process in the Prescriptive Study consisted of two phases using a combination of quantitative and qualitative research. The first phase, based on quantitative research, obtained in-depth understanding and detailed identification of 540 design cases within ideation in response to the identified requirements. In the second phase, the solution concept in the previous stage was developed using qualitative research, iteration cycles of reviewing, revision, combination, testing, and evaluation of facts in empirical studies within literature. The resulting solution consisted of three variation versions of general methods that facts in literature applied. The detailed context of the solution is described in Chapter 4 and Chapter 1. The evaluation stage uses experiments that required users to follow the solution developed, and obtained various quantitative and qualitative data using four stages; experiment design, data collection, analysis, and evaluation. Experiments were also designed to be conducted within two countries and with two experimental groups, to collect diverse evaluation data according to expected usage situations.

Chapter 4 - Database and perceptual mapping software

This chapter introduces the method developed to improve the creativity and ideation performance of novice designers. It develops a structured process architecture comprising three developed ideation methods according to the three stages of the ideation model provided in Figure 2.5. Based on identification of the requirements, the method, Knowledge-Enabled Design Ideation Method (KEDIM) comprising of database, perceptual mapping software, and brainstorming is developed. KEDIM aims to improve novice designers' creative ideation processes and practice based on understanding of their thought processes and activities. Information regarding KEDIM and its first and second stages is provided in this chapter.

This chapter describes the development of KEDIM and then explains in detail the first two stages. The chapter begins by introducing the requirements of KEDIM along with gaps between practical designers and design literature in Section 4.1. The research process and results are given to define a detailed solution concept based on empirical experience and assessment in Section 3.4. These findings are drawn together in the systemic architecture of KEDIM comprising three general ideation methods. After that, two stages of KEDIM are explained in turn, followed by their major considerations, solution concept, and outcomes with examples in Section 4.2 and 4.3. In addition, a third stage is presented in Chapter 1.

4.1 Needs and requirements for a method for improving design ideation process

KEDIM mainly considered the gap between research and practice within design ideation. The requirement for an ideation method with a comprehensive ideation process arose because the majority of ideation methods focus on a specific part of ideation with lack of consideration for other methods. On the other hand, literature provides systematic ideation strategies based on evidence from empirical studies. With respect to practising designers, a wider range of ideation methods is required to promote creative ideation activities. Furthermore, newly developed ideation methods have not been widely used in practical fields because users faced difficulties learning how to use them, and are mainly restricted to using a limited number of conventional ideation tools and methods. These contexts were drawn into the revision of general ideation methods based on research results in literature.

The research developed an ideation method that provide an overall process architecture from the brief to solution concept generation in order to improve novice designers' ideation performance. As a result, the method, Knowledge-Enabled Design Ideation Method (KEDIM) was developed comprising of database, perceptual mapping, and brainstorming in order to establish systematic ideation stages. Figure 4.1 illustrates the framework of KEDIM and how common methods were developed and structured to establish a systematic ideation process. Database and perceptual mapping methods were selected as appropriate resources from which to draw analogies through logical exploration, the first and second stages of KEDIM. Perceptual Mapping Generation Software (PMGS) is specifically focused on drawing analogies through the presentation of visual information of the populated database according to the user's intention, with the aim of supporting the leap to the next stage.

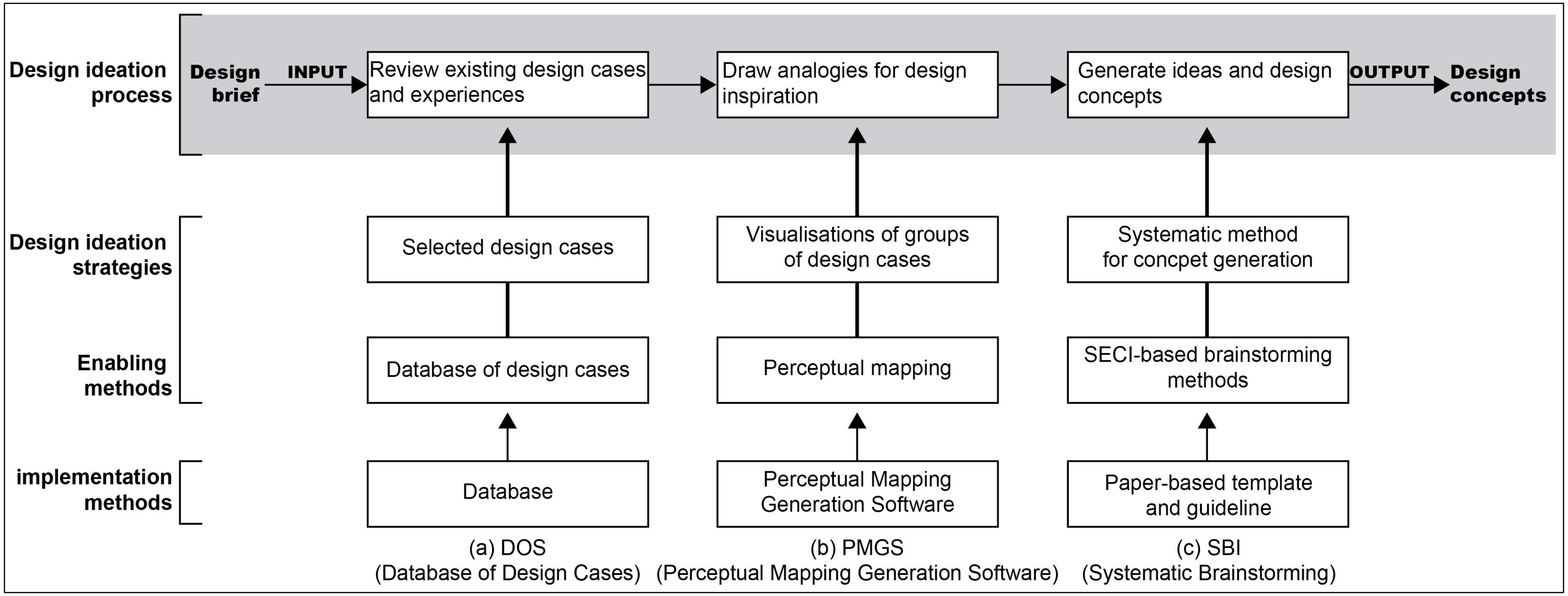


Figure 4.1 Knowledge-Enabled Design Ideation Model (KEDIM) structure

Brainstorming, the third stage of KEDIM, was chosen for designers' intuitive and easy solution concepts generation based on drawing analogies from the second stage. The development to the brainstorming process was performed due to the limitations of relying on personal abilities or random moments of inspiration for form generation within an unsystematic process. The SECI theory (Nonaka et al., 2000) was used to build a brainstorming paper template involving a structured form-generation process. In the thesis, the third stage of KEDIM refers to the Systematic Brainstorming (SBI). The detailed description of the development process and outcomes of the first and second stages of KEDIM, Database of Design Cases (DOS) and Perceptual Mapping Generation Software (PMGS), will be introduced in Section 4.2 and 4.3. The third stage, Systematic Brainstorming (SBI), will be introduced in Chapter 1.

4.2 Database of biologically inspired design cases for design case study

This section describes the development of the database of biologically inspired design cases and its associated database schema. Design cases are a commonly used method at the initial ideation stage in order to analyse existing designs with respect to learning about developmental processes, results, and assessment of solutions, and designers draw analogies by reviewing cases in response to the design brief. Despite the design cases method having been widely used in the initial stage of ideation, a lack of systematic guidelines causes limitations in ideation processes, especially for novice designers. Design case data leaves designers able to collect only partial case information, and means that they may not recognise the important facts, or perceive distorted information, rather than the correct information. Designers also rely on their memory when reviewing information of design cases. This situation can be risky at the initial ideation stage because what follows started from incorrect information. In response to these limitations, the Database of Design Cases was developed in order to provide accurate design cases for use in obtaining analogies as design inspiration.

Inspiration is core to problem framing and solution exploration in response to a design brief as a core part of the ideation process, and it is triggered by stimuli from internal resources (e.g., individual background and experiences) and external resources (Vasconcelos et al., 2017). The aforementioned limitations can cause designers to focus on superficial information of design cases which significantly hinders the learning process relating to fundamental properties of cases. This situation can cause fixation and lack of inspiration. In response, a Database of Design Cases (DOS) was developed with the aim of supporting the establishment of analogies generated from quantitative and accurate case information. Making analogies can encourage grouping and connecting ideas in unexpected ways, which may enhance ideation (Ulrich & Eppinger, 1995; Ball & Christensen, 2009; Stacey, Eckert, & Earl, 2009) and lead to the development of new products (Perkins, 1997). The Database method involves structured data collection in order to systematically build, manage and utilise a mass of data and information (Hammer and Mc Leod, 1981). This method has been widely used in various industries and research fields, although not widely in design ideation fields.

4.2.1 Database schema for design cases

A database schema for four groups of design cases was established, and populated using biologically inspired design cases. The structure of the database schema developed consists of two parts (Figure 4.2). The first part (groups 1 and 2 in Figure 4.2) deals with objective design case information, such as production year, scale, design resources, and so on. The given fixed lists of objective case information help prevents misunderstanding or bias which is caused from reviewing only partial case information.

After completing this first part, users can implement subjective evaluation. It can be modified in response to a design brief or for individual reasons in the second part. In this research, the developed database schema focused on the specified theme 'relationship of biologically inspired design and manufacturing background'. The use of specific themes supports the researcher in focussing on the purpose of the database. It can be modified for more general usage in the future (Blessing and Chakrabarti, 2009).

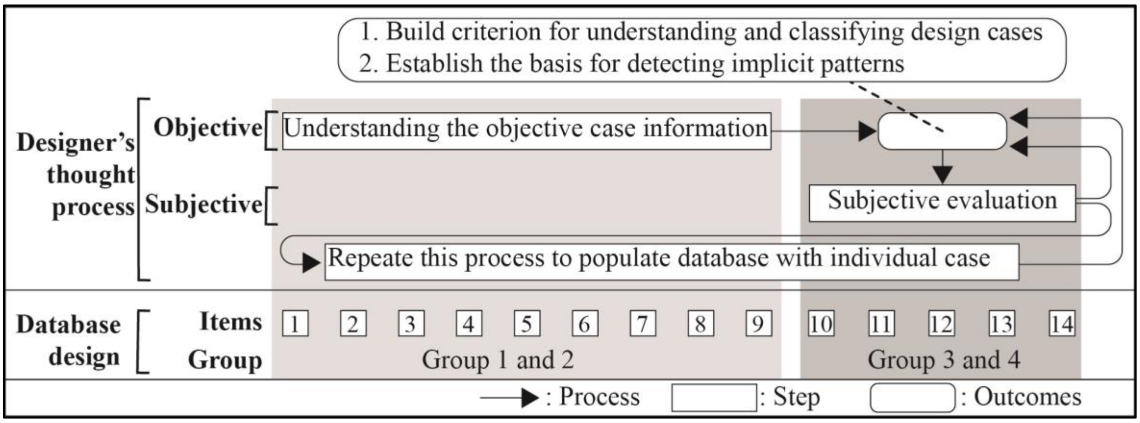


Figure 4.2 Structure of database schema for DOS

Four database query groups were covered to systematically guide users from understanding the objective design cases to building their own criteria for subjective evaluation along with meta-data for each design case. The results of evaluation or justification of design cases through this database method supports the designer in building their own unique perspective to understand and classify design cases, which is the basis for recognition of implicit patterns in the case of the populated data (see Figure 4.2). The following and Table 4.1 give details of the four groups of data.

- Group 1 (basic case information) contains unique case information. Items 2 to 5 are commonly used in general perceptual map cases. 'Scale (cm cubic)' (item 6) is the effective criterion to recognise 3D design shapes from the limited data such as picture (item 2) and video, and prevent distortion of objective information (Lawson, 2006).

- Group 2 (the design development environment) deals with the major design development sequential process in perspective of the designer. In detail, item 7, design resources, is how designers obtain their main inspiration or motivation. Item 8, development environment, is the working place where designers develop forms in the design ideation process. And, item 9 is what technology or tools were used for fabricating the design outcomes. The option lists have three main aspects, the leading edge, tradition, and both, and the answer list was established using the experience and results from the prototype perceptual map experiment.

- Group 3 (functional and aesthetic characters) includes the evaluation data of design outcomes, while group 2 deals with the design development process. This group is the first stage to ask for the subjective evaluation of four design outcomes. As a result, this group will be relevant to users after understanding the objective data in group 1 and 2. Systematic guidelines with minimum options will be informed that are based on the prototype perceptual map experiment and theories of Julian Vincent at the University of Bath (Vincent, 2009; Vincent et al., 2006).

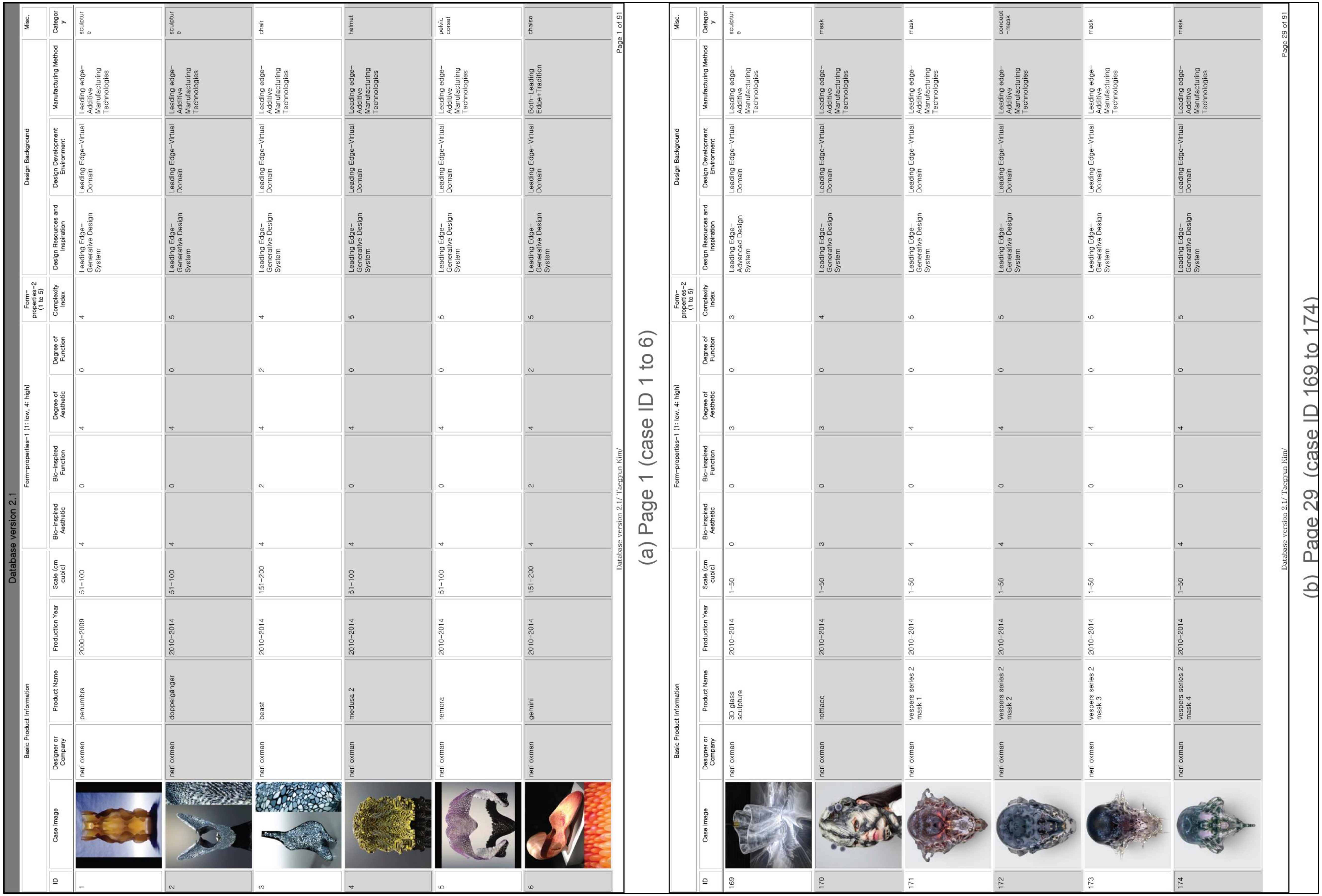
- Group 4 concerns the degree of complexity of the solution. Similarly to group 3, it also relies upon subjective evaluations that cannot be quantified. However, this has important meaning in that this property was detected during the repeated populating of groups 1 to 3. The guideline of 5 evaluation stages was designed as a result of use and experience of the suggested database and perceptual map generation software. Following is the detailed context. 1 means the simplest outcomes which consist of basic shapes (circle, sphere, corn, cube, misc.), 4 means existing complex shapes and refers to current design background or cases, and 5 is a new genre of complexity based on state of the art technologies.

Table 4.1 The structure of DOS

Elements	Input method	Available option list		
Group 1. Basic Case information				
1.Case ID	Type text	Type sequential increasing number (1, 2, 3…)		
2.Case image	Insert image			
3.Designer (company)	Type text			
4.Product name				
5.Production year	Predefined option	2010-2017, 2000-2009, 1990-1999, 1980-1989, …		
6.Scale (cm cubic)		301-, 251-300, 201-250, 151-200, 101-150, …		
Group 2. The design development environment				
7.Design resources	Predefined option	Leading Edge side	Generative Design System	
			Advanced Design System	
		Traditional side	Personal Experience and Inspiration	
			Mechanic based Design System	
		Both	Leading Edge+Tradition	
8.Development environment	Predefined option	Leading Edge side -Virtual Domain		
		Tradition side -Real Domain		
		Both -Leading Edge+Tradition		
9.Manufacturing method	Predefined option	Leading edge side	Additive Manufacturing Technologies	
		Traditional side	Bespoke	
			Handmade	
		Both	Leading Edge+Tradition	
Group 3. Form property 1 (functional and aesthetic characters)				
10.The degree of biologically inspired aesthetic	Predefined option	1	Imitate nature directly or simply	
		2	Imitate nature with understanding	
11.The degree of biologically inspired function		3	Extract core elements from nature	
		4	Extract core elements from nature with high efficiency	
12.The degree of Aesthetic	Predefined option 12: Left 13: Right	1	Not attractive	low efficiency
		2	Normal	similar efficiency
13.The degree of function		3	Attractive	improved efficiency or achievement of multi-faceted development (AMD)
		4	Definitely attractive	improved efficiency and AMD together
(0: non-applicable, 1: the lowest, 4: the highest)				
Group 4. Form property 2 (complexity of solution)				
14.Complexity of solution	Predefined option	1,2,3,4,5 (1: the simplest, 5: the most complex)		

4.2.2 Populating the database

The database design in Table 4.1 was built using Microsoft's Access 2016 64bit software. Then, data on 540 biologically inspired designs (total 7,560 data elements with 14 items per case) in diverse areas (art, consumer products, automobile, robots and misc.) and over a period (1899~2017) were used to populate biologically inspired design database version 2.1 (see Figure 4.3 and Figure 4.4). There are some acronyms used i.e., FP-1, which refers to form property 1 in order to increase readability in this paper. The full names were used in the original documents in line with the database structure in Table 4.1.



Database version 2.1

ID	Case image	Designer or Company	Product Name	Production Year	Scale (cm cubic)	Bio-inspired Aesthetic	Bio-inspired Function	Degree of Aesthetic	Degree of Function	Complexity Index	Design Resources and Inspiration	Design Development Environment	Manufacturing Method	Category
	Basic Product Information					Form-properties-1 (1: low, 4: high)				Form-properties-2 (1 to 5)	Design Background			Misc.
1		neri oxman	penumbra	2000-2009	51-100	4	0	4	0	4	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	sculpture
2		neri oxman	doppelgänger	2010-2014	51-100	4	0	4	0	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	sculpture
3		neri oxman	beast	2010-2014	151-200	4	2	4	2	4	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	chair
4		neri oxman	medusa 2	2010-2014	51-100	4	0	4	0	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	helmet
5		neri oxman	remora	2010-2014	51-100	4	0	4	0	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	pelvic corset
6		neri oxman	gemini	2010-2014	151-200	4	2	4	2	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Both-Leading Edge+Tradition	chaise

Database version 2.1/ Taegyun Kim/ Page 1 of 91

(a) Page 1 (case ID 1 to 6)

ID	Case image	Designer or Company	Product Name	Production Year	Scale (cm cubic)	Bio-inspired Aesthetic	Bio-inspired Function	Degree of Aesthetic	Degree of Function	Complexity Index	Design Resources and Inspiration	Design Development Environment	Manufacturing Method	Category
	Basic Product Information					Form-properties-1 (1: low, 4: high)				Form-properties-2 (1 to 5)	Design Background			Misc.
169		neri oxman	3D glass sculpture	2010-2014	1-50	0	0	3	0	3	Leading Edge-Advanced Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	sculpture
170		neri oxman	rottlace	2010-2014	1-50	3	0	3	0	4	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	mask
171		neri oxman	vespers series 2 mask 1	2010-2014	1-50	4	0	4	0	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	mask
172		neri oxman	vespers series 2 mask 2	2010-2014	1-50	4	0	4	0	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	concept-mask
173		neri oxman	vespers series 2 mask 3	2010-2014	1-50	4	0	4	0	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	mask
174		neri oxman	vespers series 2 mask 4	2010-2014	1-50	4	0	4	0	5	Leading Edge-Generative Design System	Leading Edge-Virtual Domain	Leading edge-Additive Manufacturing Technologies	mask

Database version 2.1/ Taegyun Kim/ Page 29 of 91

(b) Page 29 (case ID 169 to 174)

Figure 4.3 Sample of the biologically inspired design database version 2.1 (page 1 and 29)

Basic Product Information						Form-properties-1 (1: low, 4: high)				Form-properties-2 (1 to 5)	Design Background			Misc.
ID	Case image	Designer or Company	Product Name	Production Year	Scale (cm cubic)	Bio-inspired Aesthetic	Bio-inspired Function	Degree of Aesthetic	Degree of Function	Complexity Index	Design Resources and Inspiration	Design Development Environment	Manufacturing Method	Category
475		KARIM RASHID	VITA FAUCET	2010-2014	1-50	1	0	1	0	1	Tradition-Personal Experience and Inspiration	Tradition-Real Domain	Tradition-Mass Production	
476		KARIM RASHID	SILK PAPER HOLDER	2010 2014	1 50	1	0	2	0	1	Tradition Personal Experience and Inspiration	Tradition Real Domain	Tradition Mass Production	
477		KARIM RASHID	KREATE BY KARIM	2010 2014	1 50	1	0	2	0	2	Tradition Personal Experience and Inspiration	Tradition Real Domain	Tradition Mass Production	
478		KARIM RASHID	3D PRINT COLLECTION-1	2010 2014	1 50	1	0	1	0	1	Tradition Personal Experience and Inspiration	Tradition Real Domain	Leading edge Additive Manufacturing Technologies	
479		KARIM RASHID	3D PRINT COLLECTION-2	2010-2014	1-50	1	0	1	0	1	Tradition-Personal Experience and Inspiration	Tradition-Real Domain	Leading edge-Additive Manufacturing Technologies	
480		KARIM RASHID	3D PRINT COLLECTION-3	2010-2014	1-50	1	0	2	0	1	Tradition-Personal Experience and Inspiration	Tradition-Real Domain	Leading edge-Additive Manufacturing Technologies	

Database version 2.1/ Taegyun Kim/

Page 80 of 91

(c) Page 80 (case ID 475 to 480)

Basic Product Information						Form-properties-1 (1: low, 4: high)				Form-properties-2 (1 to 5)	Design Background			Misc.
ID	Case image	Designer or Company	Product Name	Production Year	Scale (cm cubic)	Bio-inspired Aesthetic	Bio-inspired Function	Degree of Aesthetic	Degree of Function	Complexity Index	Design Resources and Inspiration	Design Development Environment	Manufacturing Method	Category
535		ANDREW RAFFEI	EMOTO GROVE	2010-2014	1-50	0	0	1	1	2	Tradition-Mechanic based Design System	Leading Edge-Virtual Domain	Leading Edge-Additive Manufacturing Technologies	
536		LOCAL MOTORS	STRATI	2010-2014	300-	0	0	1	3	1	Tradition-Mechanic based Design System	Leading Edge-Virtual Domain	Leading Edge-Additive Manufacturing Technologies	
537		Matthew Plummer Fernandez	Digital Natives SERIES	2010 2014	1 50	0	0	3	0	3	Tradition Personal Experience and Inspiration	Leading Edge Virtual Domain	Leading edge Additive Manufacturing Technologies	
538		Michelin	CONCEPT VISION MICHELIN	2010 2014	51 100	3	3	3	3	4	Leading Edge Generative Design System	Leading Edge Virtual Domain	Leading edge Additive Manufacturing Technologies	
539		DUS Architects	Dutch EU building	2010-2014	300-	1	0	3	2	2	Leading Edge-Advanced Design System	Leading Edge-Virtual Domain	Both-Leading Edge+Tradition	
540		Hutzenvold Chloe	Edible Growth project	2010-2014	1-50	2	2	2	3	3	Tradition-Personal Experience and Inspiration	Both-Leading Edge+Tradition	Both-Leading Edge+Tradition	

Database version 2.1/ Taegyun Kim/

Page 90 of 91

(d) Page 90 (case ID 535 to 540)

Figure 4.4 Sample of the biologically inspired design database version 2.1 (page 80 and 90)

DOS was populated firstly with items 2 to 9 as objective elements (basic case information and design development environment group), and then evaluates item schema 10 to 14 as subjective elements according to the suggested objective guidelines (functional and aesthetic characters and the complexity of solution). Groups 2 and 3 (the design development environment and functional and aesthetic characters) were designed in order to research interplays between design development environment and its outcomes in order to understand the design concept generation method, and aid its understanding.

The database schema, which is a classification scheme, increases the quality of analogies by supporting systematic learning of design cases. It leads designers to explore diverse design cases involving specific properties which are required from the design brief, and adapt them into solution concepts. Users are able to search the wide range of populated data through 1) specific key words, 2) selecting a predefined option, or 3) browsing images. After this they can review the detailed information of relevant design cases. It allows the user to approach diverse kinds of information in different categories such as type of product, form-properties, or design background, and this exploration supports creative ideation performance and mitigates fixations through improve analogies in the process of problem framing and solution explanation (Sein et al., 2011; Wiltschnig et al., 2013). This is illustrated here with the example of a water bottle.

1) Users can search relevant key words (e.g., water bottle, bottle, or tumbler) to review design cases which are closely related to the design object required.
2) They also can select a predefined option. For example, if the design brief requires a unique form of water bottle, users can select either ‘cases which are applied additive manufacturing technologies’ or ‘cases which achieve complex solutions’ (ID 9 or 14 in Table 4.1 The structure of DOS).
3) They can browse images to look through cases.

The next stage of KEDIM supports these explorations through perceptual mapping - see the following section for detailed context.

4.2.3 Further development of database schema

The database schema was designed to provide systematic population, learning, and exploration of a wider range and higher number of pieces of design cases information in accordance with indexing or classification. Having been used for this purpose in this research, further developments and opportunities were identified. The range of search methods supported could be increased. Achieving this would require each case to containing a set of specific data lists to enable coverage of universal case categories. In addition, the design cases in the database could be put to wider purpose than originally intended by extending the way in which the cases are indexed. Populated case data indexed in different ways could be used to support compound explorations across multiple classifications of product or other factors. The ranges of data obtained would enhance reasoning through increased stimulation, and support better adoption of requirements (Maher and De Silva Garza, 1997). However, further work would be needed to identify the most useful indexing schemes to add.

4.3 Perceptual Mapping Generation Software

This section introduces the requirements and outcomes of the third stage of KEDIM, Perceptual Mapping Generation Software (PMGS). PMGS provides a structured solution concept generation process based on drawing analogies in the first and second stages of KEDIM. The PMGS is explained in detail followed by the translation process from DOS (first stage) to PMGS (second stage), software configuration, and outcomes generated. In particular, the selection of specific raw data or cases from the database, and their appropriate presentation according to designers' needs can increase analogies due to increased stimulation from customised information. For instance, processed data from the database can offer information from a comprehensive perspective (e.g., trends or developmental direction of cases) to a microscopic perspective (e.g., specific properties which relate to manufacturing background). Perceptual mapping was selected as the most suitable method to satisfy the aforementioned need.

4.3.1 Proposed perceptual mapping method

Perceptual Mapping Generation Software (PMGS) is the visualisation method that brings together selected design cases from the DOS database and presents them in a way that enhances novice designers' abilities to draw analogies. The development of PMGS is used to place design case images according to the designer's requirements as the axis definition from DOS outcomes. This process is simple, yet it is a laborious task which has little relationship with design ideation. PMGS is used in three stages: define axis and coding systems, and select cases. The coding systems is a unique data marking method that is used in order to deliver a wider variety of data to counter against the limited amount of delivery information, and its detailed context is described in the following sections. The main benefit of PMGS is the ability to easily manipulate large databases through a classifying, aligning and grouping process with increased display of design case information through coding systems. PMGS used the data in DOS as resources to generate perceptual mapping outcomes (Table 4.2).

Table 4.2 Data type link definition from DOS data to PMGS

Three data types in DOS	▶	Available application in PMGS
Case image	▶	Case image on perceptual map
Typed text	▶	No relationship
Fixed answer types	▶	Chart axis
	▶	Coding (except used elements for above chart axis)

4.3.2 Coding system

Prior to describing PMGS in detail, it is worthwhile to introduce the coding system, because it is involved in PMGS description and perceptual mapping outcomes generated by PMGS. The coding system is the unique visualisation method in PMGS that marks database information on the case image of the perceptual map. It is a solution for the defined limitation, that only a small amount of information can be delivered (case image and position on axis). Compared to the general case displaying images only (Figure 4.5 a), coding systems deliver database information through a circular (Figure 4.5 b-1) or square frame (Figure 4.5 b-2) on the case image, and the maximum amount of available data is five. In comparison to a general perceptual map displaying three pieces of visual information (case image, X and Y axis), this software can deliver up to eight pieces of visual information with coding systems. There are four simple steps in PMGS to generate coding, and detailed context will be given in following sections.

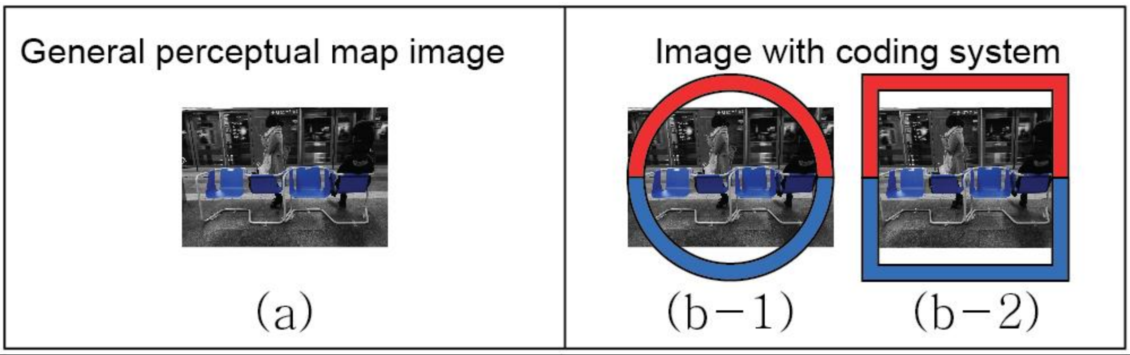


Figure 4.5 Concept of coding: example of marked design cases on the perceptual map (a) general perceptual map, (b-1) coding system: circle frame including two data, (b-2) coding system: square frame including two data.

4.3.3 Software configuration

PMGS user interface consists of two areas. The left side is used for the definition of perceptual map generation (Figure 4.6 a) and the right side for showing its real-time results (Figure 4.6 b).

Figure 4.6 Capture image of main page of Perceptual Mapping Generation Software (PMGS)

The definition section in PMGS (Figure 4.6 a) consists of five subsections as follows.

- Chart structure: It offers check lists from the imported DOS data in order to design perception maps. This process is conducted with three steps (1. Define axis, 2. Define cases and 3. Define coding) which is almost the same process as that currently used in general handicraft.
  In particular, defining coding, the third step, is unique, and it can be defined as following: first, the user selects database elements, and designs relevant data into colour or text options before appointing detailed coding style such as coding shape (circle or square frame), and the start point of coding and rotation direction (clockwise or counter clock wise). Figure 4.7 is the capture image of software for coding definition, and this definition was used for outcomes in Figure 4.8 and Figure 4.9.
- Library: The design case database (the DOS outcome) can be imported to this software as the first step according to data link definition, as previously described in Table 4.2.
- Save: The definition from the chart structure subsection can be saved.

- The chart systems: each defined chart structure in the saved subsection can be combined to easily make multiple perceptual map outcomes from one design case and coding systems.
- Export: the result on the real-time window can be exported. The available maximum is A1 size (841*594mm) with 300dpi (dots per inch) resolution. These results can be saved in three formats (PNG, JPG and PDF). In the case of PNG, it includes a transparent background for additional editing works.

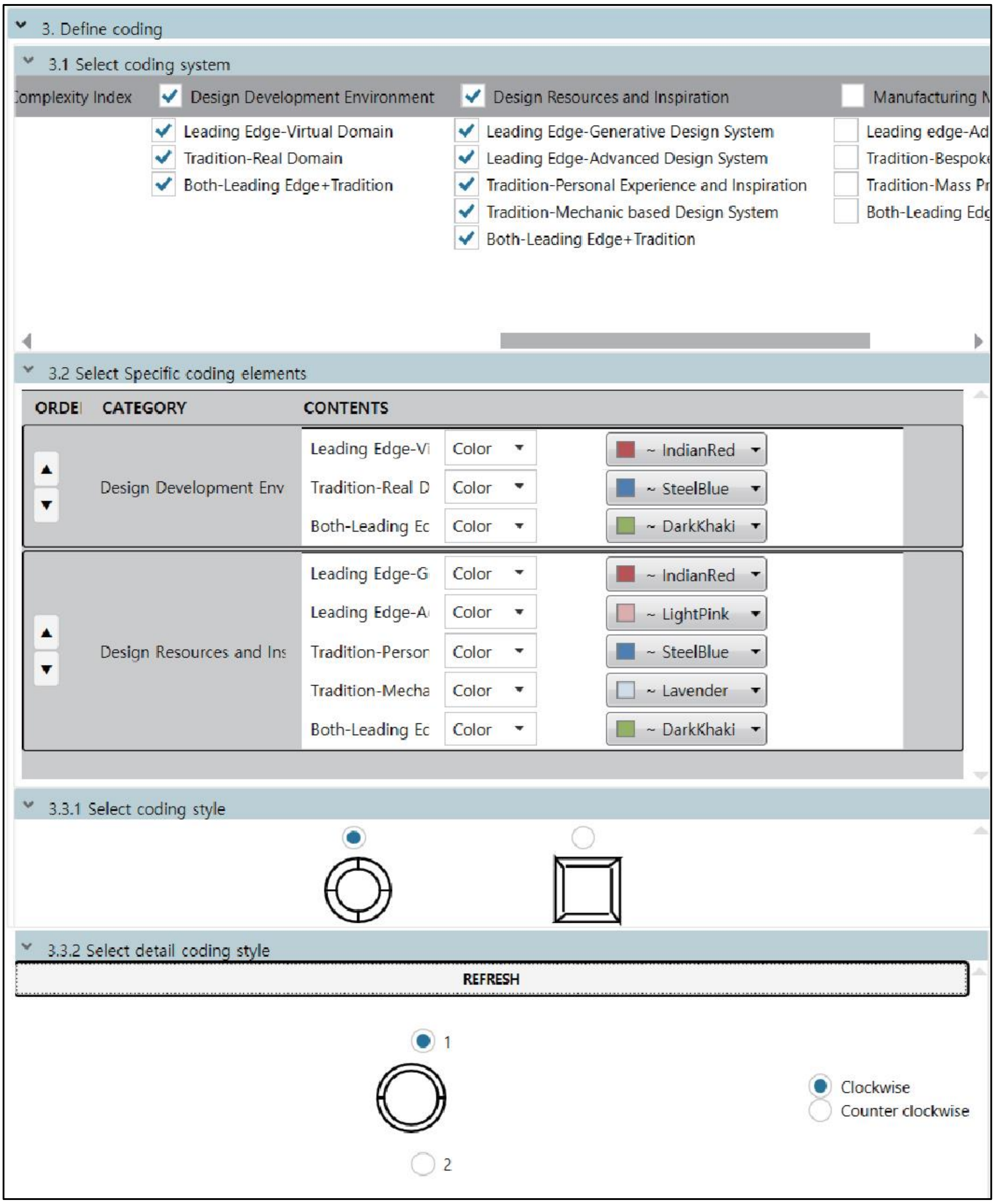


Figure 4.7 Define coding stage in PMGS

The real-time result section (Figure 4.6 b) illustrates the perceptual map outcomes in real time from the defined works. Users can zoom in and out, and move the real time result to explore results. The save chart button can easily export real-time results with a fixed option (A1 size, 300 dpi, PNG format) in order to immediately capture the inspired outcomes and idea.

4.3.4 Design of the perceptual mapping generated from software

PMGS is used to generate perceptual mapping from the biologically inspired design database version 2.1 in Section 4.2.2. Figure 4.8 provides an example of one of the generated outcomes. It was designed to place all 540 cases according to the X axis (production year) and Y axis (complexity of solution). The coding, which is located on each case image, is shown by a circular frame with separated upper and lower parts that refer to the development environment (schema item 8) and manufacturing method (schema item 9) respectively. The colours of red, blue, and green indicate the leading edge side, traditional side, and both. This perceptual mapping outcome provides sources and clues for analogical interpretation. A detailed explanation is given in Chapter 6. Additionally, 12 of 540 cases in the specific production years (1950 – 1979) were not displayed on Figure 4.8 and Figure 4.9 in order to increase the readability of this paper.

Figure 4.9 shows the key points of the design case images with coding systems re-placed according to the variable factor (Y axis: (a) scale (cm cubic), (b) complexity of solution). The two design cases (ID 171 and 276. See Figure 3.4 for detailed information of the two cases) were replaced on the Y axis section (Figure 4.9 a, and b) in the same X axis area (production year, 2010-2014) according to the different Y axis.

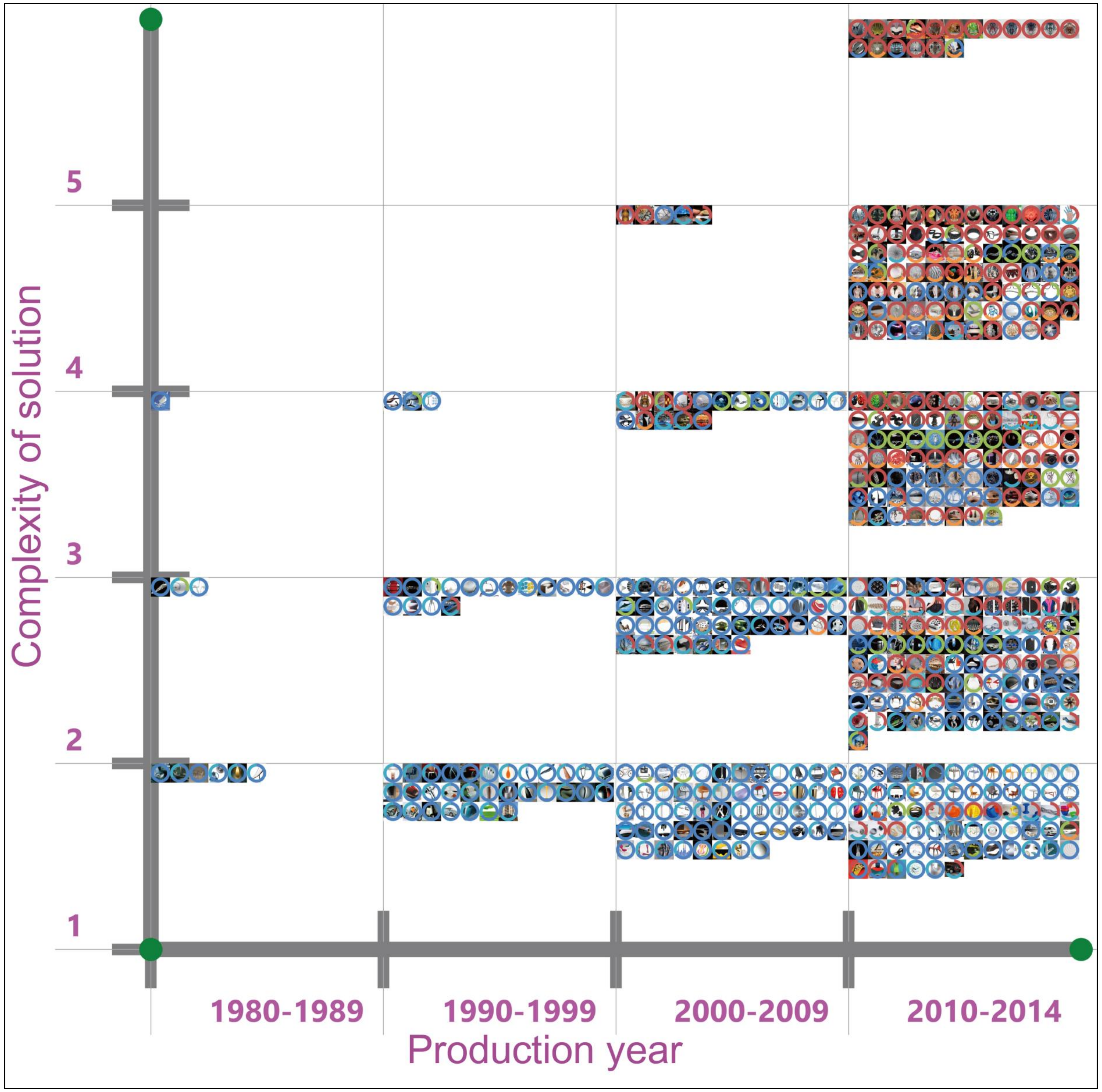


Figure 4.8 The example of outcomes including 540 design cases from perceptual map generation software (size: 594*594mm. resolution: 300dpi)

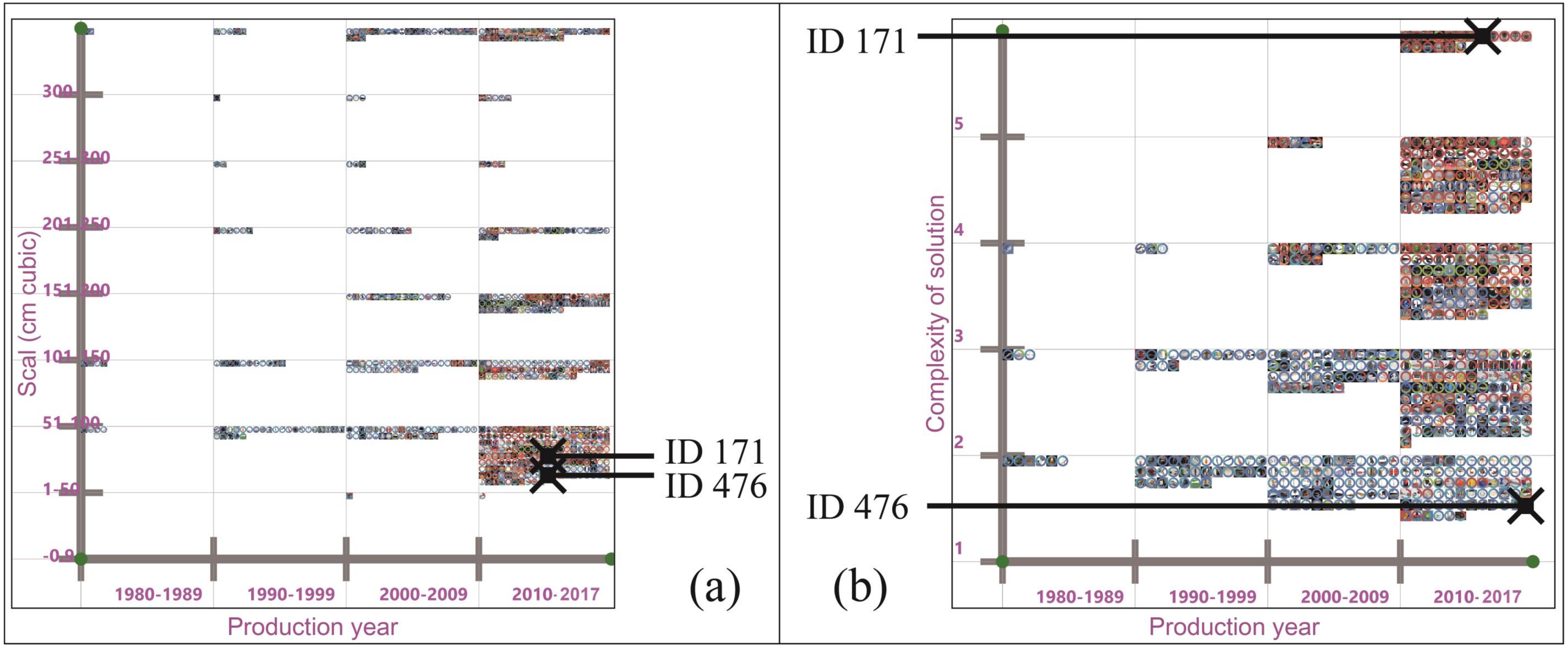


Figure 4.9 The movement of cases according to different Y axis

In brief, according to the empirical experiments, PMGS showed noteworthy results relating to time consumption, compared to the empirical research provided in Table 3.5. PMGS took around five minutes to import the biologically inspired design database (540 cases, 7,560 data), define perceptual mapping (axis and coding), and export image (A3 size and 300dpi resolution) in empirical study. It took 1 minute to change the definition of perceptual mapping and the exported image from that shown in Figure 4.9 a to b. On the other hand, empirical research took 2 weeks for generation of perceptual mapping including 150 cases. It was also assumed that the credibility of outcomes from PMGS was higher than the empirical research outcomes, because data was systematically established on database schema developed in the previous stage (DOS). It should be noted that the aforementioned working time in PMGS did not included time for establishment of the database which is considered as the first stage of KEDIM (DOS).

4.4 Summary

The designs of the database and perceptual mapping software introduced in this chapter form part of the contribution to knowledge in this thesis. The database was populated with 540 design cases which can be used to provide inspiration in design ideation processes. In contrast to current practice, the design cases are drawn together in a structured process and meta-data is added to support their use by designers. The perceptual mapping software is an example of a software tool that uses this meta-data to support users to navigate the database and visualise the data in novel ways e.g. through analogies that are relevant to the design task, which is essential for effective ideation. The drawing of these analogies is developed through a structured concept generation process for the purpose of enhancing creative solution concept generation through Systematic Brainstorming (SBI), the third stage of KEDIM. Detailed information on SBI is provided in detail in the next chapter.

Chapter 5 – Systematic Brainstorming

This chapter provides a detailed description of the third stage of KEDIM, Systematic Brainstorming (SBI), along with research background, development process, and outcomes including guidelines. This part of KEDIM aims to provide a structured solution concept generation process with an easy method of use based on drawing analogies from the previous two parts, DOS, the Database of Design Cases, and PMGS, the Perceptual Mapping Generation Software.

The chapter begins by introducing the background of a selected general ideation method in Section 5.1. Section 5.2 reviewed benefit and risk of general brainstorming in order to clarify the desired goals of the third part of the solution. These contexts then provide the requirements for the development stage of KEDIM, SBI. The development process to integrate the SECI theory into the paper template for brainstorming, and user guidelines are explained in detail from Section 5.3 to 5.6. The chapter closes with a summary of previous sections in Section 5.7.

5.1 Brainstorming method

Brainstorming is a widely used ideation method that is familiar to the majority of novice designers (Dugosh et al., 2000; Paulus et al., 2011). It has the benefit of being an intuitive and easy way to freely express and develop ideas from experiences and analogies. Designers write or draw by pen on paper to express their thought (component part in Figure 5.1) (Dugosh et al., 2000; Goldschmidt and Smolkov, 2006; Hernandez et al., 2010; Paulus et al., 2011). Based on these activities, designers generate wide-ranging ideas along with re-interpretation of varied internal/external sources involving analogies with the aim of achieving creative solutions while mitigating fixation on criticism and assessment (Paulus et al., 2011) (concept part in Figure 5.1).

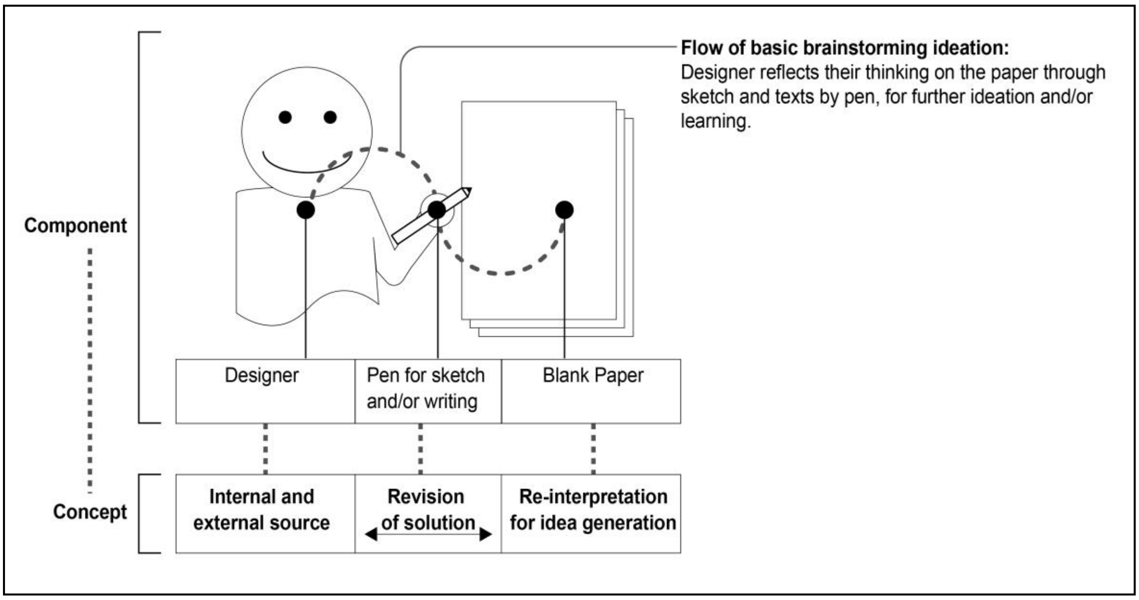


Figure 5.1 The basic component and concept of brainstorming

As described in Figure 5.1, paper is the core medium in brainstorming through which one can interpret designers' understanding and thoughts from the various obtained sources amassed with the aim of producing novel idea generation along with inspiration, motivation, and revision. Even though blank paper has been generally used in order to promote independent ideation activities, it can cause significant limitations for novice designers (Dinar et al., 2015). It is because the majority of novice designers possess insufficient abilities, strategies, skills, and accumulated experience of ideation, and when confronted with a piece of blank paper this can cause concurrent actions with vague objectives (Ho, 2001; Ball et al., 2004; Dinar et al., 2015). In this context, basic brainstorming methods tend to lead to unsystematic processes for solution concept generation from drawing analogies. These issues are also particularly affected by the fact that brainstorming heavily relies on personal abilities for form/shape generation for idea development. All of these aforementioned limitations impact on ideation activities and learning when brainstorming is used by novice designers.

In spite of the aforementioned limitations, paper still has important potential as a medium that enables the users' ideation process to be led according to the intention of the researcher. Therefore, revision of brainstorming aimed to create a paper template in order to provide an intuitive and systematic idea generation process. The development process and outcomes will be provided in the following sections.

5.2 Requirements for the brainstorming tool

The desired goal of SBI was to integrate a systematic process based on a high degree of ideation freedom as the major benefit of brainstorming. It was drawn to the requirement for development of a set of specific ideation themes. In response to these desired goals, the SECI theory (Nonaka et al., 2000) was selected as an appropriate solution, as a result of iterative reviewing and application based on literature review and assumption (Blessing and Chakrabarti, 2009).

SECI is a knowledge creation model which can be used to define core context from cases to refine for the desired solution knowledge (Nonaka et al., 2000) (see Figure 5.2.a). SECI is implemented through four sequential steps; Socialisation, Externalisation, Combination, and Internalisation. In the Socialisation stage, cases are explored with the aim of extracting core contexts, and it aims to reach a higher degree of tacit knowledge by accumulation of context and cases. The obtained tacit knowledge from cases is articulated to explicit context at the Externalisation stage, and then integrated to develop an appropriate solution concept and context in response to the desired goals in the Combination stage. They are finally refined into one core solution as tacit knowledge at the Internalisation stage. The one cycle consisting of these four stages is repeated leading to the development of effective solution knowledge (see Figure 5.2.a).

This conceptual framework is important within design and ideation, providing specific themes with perspective of overall processes for supporting idea generation processes within academic, practical and industrial settings: for example, design of higher education curricula (Whelan et al., 2017; Chootongchai and Songkram, 2018), design of learning environments (Mohamad et al., 2016), customised design thinking models (Bork et al., 2017), and product development (Sakellariou et al., 2017). However, it is more frequently used for the development of scenarios and functions rather than design ideation itself. As a result, SECI theory needs to be refined for use in design ideation, and its development process and outcomes are provided in the following sections.

5.3 Application of SECI theory into brainstorming paper template

A refined SECI theory for design ideation using brainstorming was implemented based on understanding its properties to integrate them into a variation version of brainstorming to reach desired goals. Two major differences were identified: existence or nonexistence of given stages, and users' method of expression for re-interpretation. Ideation using brainstorming is implemented following the user's stream of consciousness without applying specific stages. Users mainly expressed their thoughts through sketching with re-interpretation. On the other hand, SECI theory provides a knowledge generation model with four stages in which users mainly write text to express their thoughts for solution development. For instance, when using SECI in design ideation, text-based expression cannot well illustrate the shape and forms which are required, and cannot provide sufficient stimulation during ideation. This is because the given four stages are too general and vague for novice designers' ideation. These differences were therefore considered as part of this investigation and guidelines will be explained in Section 5.5 and 5.6.

The differences between guidelines, process, stages, and method of expression in brainstorming and SECI need to be considered together with the aim of combining their benefits to achieve the desired goals of SBI. In addition, these revision works were applied to specific parts of brainstorming with a view of how in parallel it develops precise results with consideration of usage environment. In the initial development process, integration of beneficial facts within SECI and brainstorming was the major concept; systematic solution concept generation process and easy method of use. These overall requirements were considered together in order to enhance users' intuitive idea generation activities and accumulation of appropriate activities through the paper template (a medium between users' thought and the desired situation in solution). This research refined specific ideation stages for the Systematic Brainstorming Ideation (SBI) method based on the SECI theory that would be suitable for novice designers. The refined process was undertaken based on understanding the objectives of each section, as well as their correlation and iteration to reach a more appropriate level (Figure 5.2). As a result, a set of specific ideation themes were derived; motifs, specific parts of design object, whole parts of design object, final ideation concept, and design objective. Table 5.1 outlines the alignment of the Systematic Brainstorming ideation with the four stages of the SECI theory: the four sequential specific ideation themes derived from the four stages of SECI theory (step 1 to 4 in Table 5.1), and one section was added due to property of ideation (step 5 in Table 5.1).

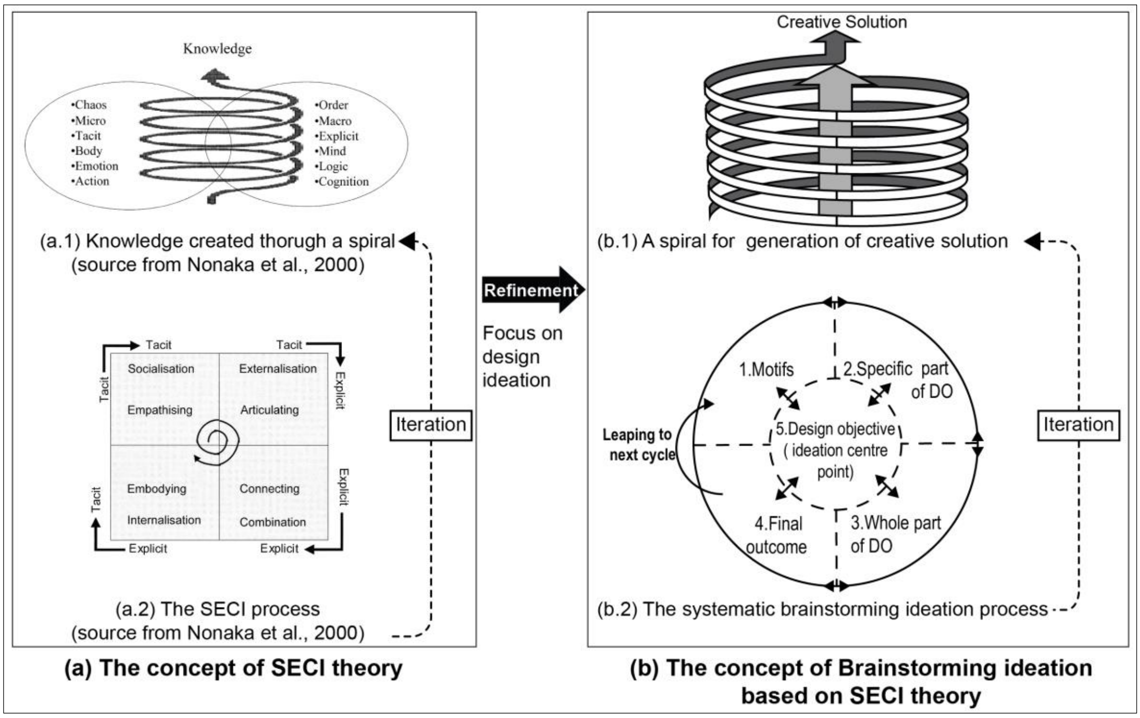


Figure 5.2 The concept of systematic brainstorming ideation process

Table 5.1 Refining from SECI to systematic brainstorming ideation stages

SECI theory		Ideation using brainstorming	
1.Socialisation	Explore the tacit knowledge as solution in response to the brief: such as motifs, case study, information or others	1.Motifs	Explore the tacit motifs or clues in response to the brief
2.Externalisation	Define the tacit knowledge to explicit information	2.Specific parts of design object	Apply motifs into specific parts of design object
3.Combination	Apply explicit information to establish solution	3.Whole parts of design object	Apply specific parts results into the whole design object
4. Internalisation	Optimise the solution	4.Final ideation concept	Ideate the design object based on the previous outcomes
		5.Design objective	Indicate design objective to consistently remind during stages 1 to 4

The placing of five specific ideation stages on the paper was considered for ease of use, because difficulty of use was one of main reasons that the new method suggested is not widely used in practical fields (Shah et al., 2000). Ease of usage also has a close relationship with users' intuitive usage and concentration as a desired solution goal. Therefore, the location of each section needs to intuitively deliver specific ideation themes and orders. Each section also needs to occupy enough space for users' re-interpretation. With this consideration, the SECI process figure by Nonaka clearly presents their concept; key context and correlation of four stages, and their iteration with a spiral mark at the centre point (Figure 5.3.a). These four stages form the basis of the paper template for SBI. It can be seen from Figure 5.3 that the method is cyclical in a similar process to the SECI model (Figure 5.3.b and c). Four specific ideation stages are sequentially located from the top-left corner of paper in a clockwise direction with order number and themes marked. Design object section (ideation central point) was placed at the centre of paper without numbering because it can be used during ideation in no specific order. This template for SBI enables effective support of users' understanding given specific ideation goals and their order. To provide enough space for expression the default paper template size is portrait A3 paper (297*420mm). In the SBI template in Figure 5.3.c, the font size is increased for readability, and Figure 5.4 is 85% of the size of the original template.

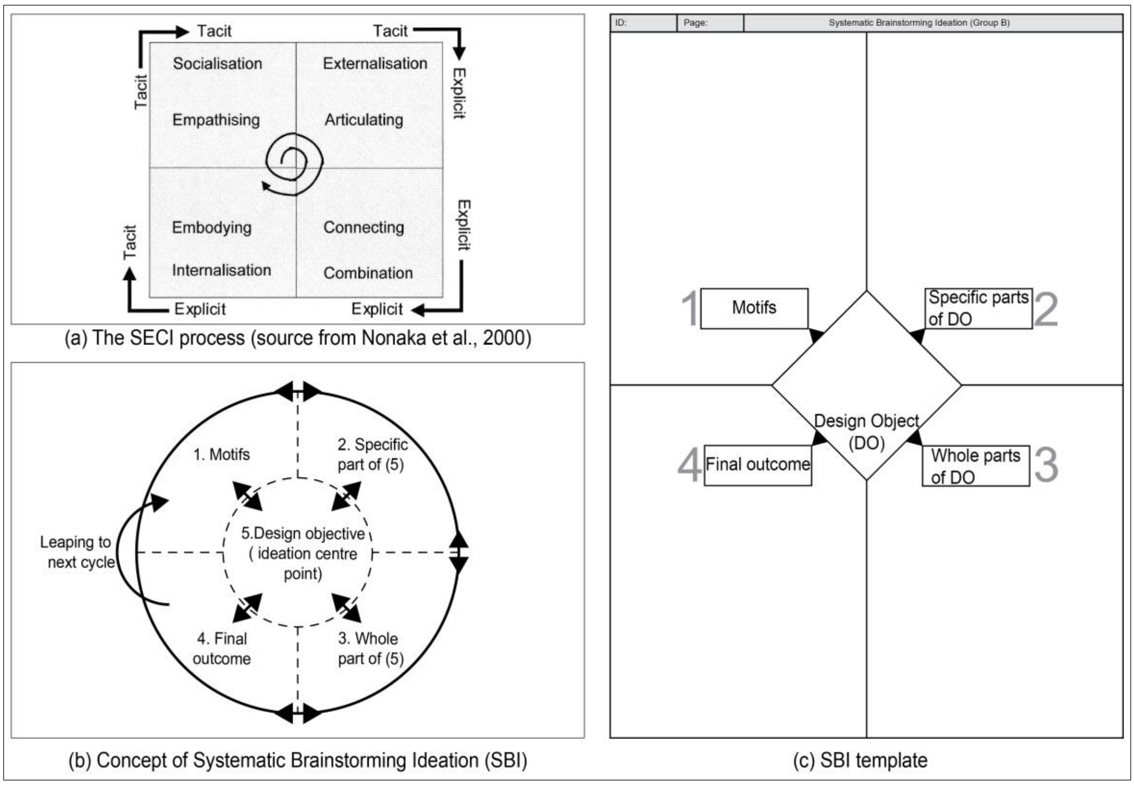


Figure 5.3 Transforming from SECI to the SBI template

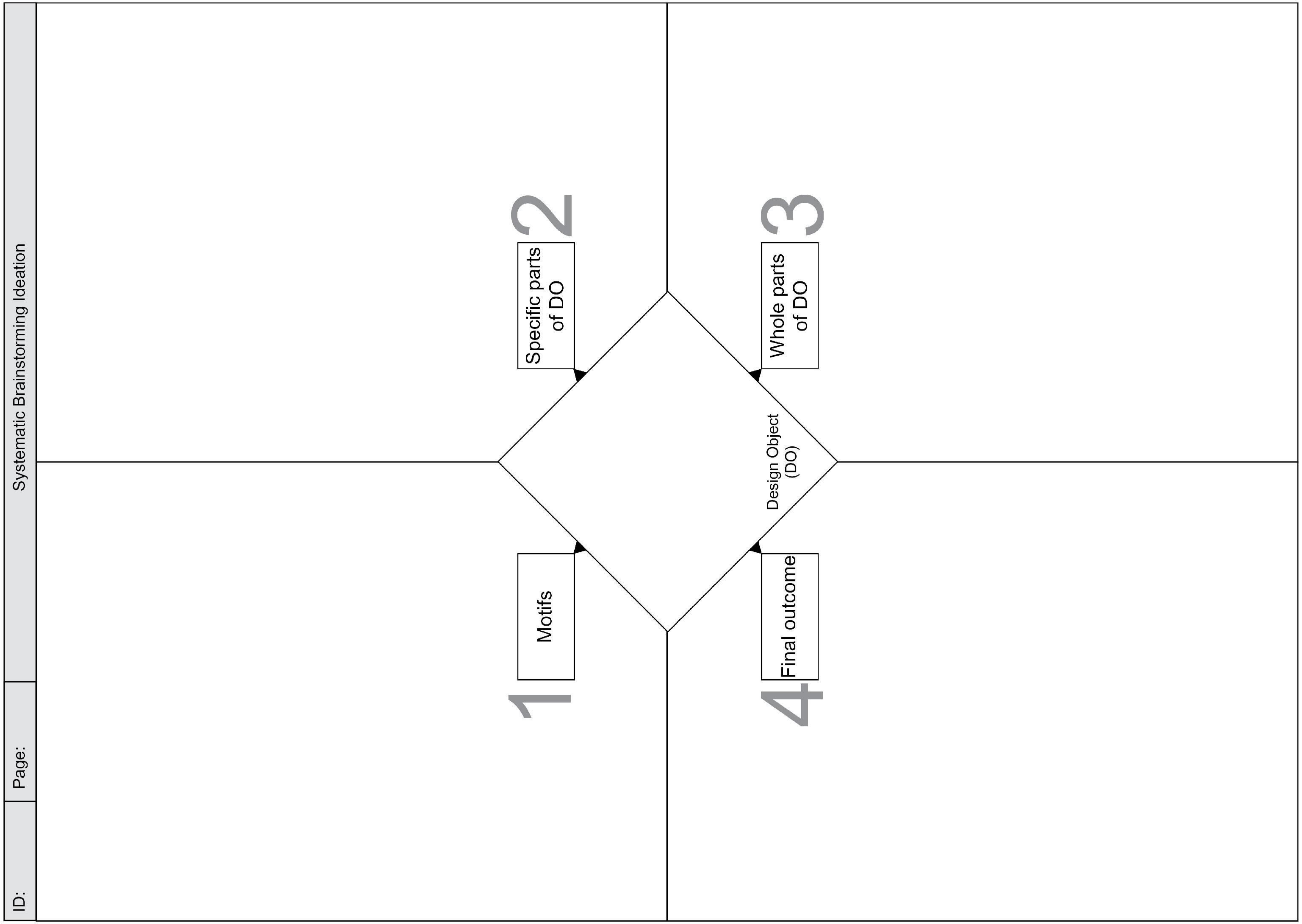


Figure 5.4 The SBI template (85% shrink size of actual template size. This template was printed on A3 paper)

5.4 Systematic Brainstorming - paper template based on SECI theory

The SBI template (Figure 5.4) is developed in order to improve novice designers' performance for solution concepts generation through a set of specific ideation themes; motif, specific part of design object, whole part of object, final concept, and design objective. At the Motif stage, the first step of the SBI template, users ideate motifs as inspiration based on drawing analogies from previous stages of KEDIM (DOS, and PMGS). Motifs refers to comprehensive context or data related to the inspiration, motifs, and clues for solution. For instance, it includes both visible (design cases and their data) and invisible data (atypical motifs such as fog, individual experience, scenario, observation, interview, and others). This stage aims to extract ideation sources for the following ideation sections in the SBI template thorough re-interpretation of obtained analogies in previous two stages.

The second stage is the Specific part of the design object, and this stage was refined based on Externalisation of SECI aiming to obtain explicit information from tacit information in the previous stage. Compared to SECI, design ideation processes needs to consider the design object and design brief in parallel. In this light, this stage requires the following ideation theme to users: application of ideas generated in the Motif stage into specific parts of the design object. In this research, specific parts of the design object refers not only to physical components but also to properties. For instance with the chair example, physical components could be support, seat, back, joints or their various combinations, and properties means the surface materials, texture, function, or others.

The third stage, the Whole part of design object section, was investigated from the Combination stage (third stage within SECI). The Combination stage aims to develop appropriate and novel solutions in response to the desired situation based on integration or revision of results in Externalisation (the second stage within SECI). In this context, the Whole part of design object stage asks users to integrate or revise results from the previous stages into the whole design of the object.

The fourth stage of SBI template is the Final concept section. It was refined from the Internalisation stage (the fourth stage within SECI) which requires revisions that were drawn from obtained ideas in previous stages for the final solution. In this context, the Final concept stage requires users to generate a final solution based on generated ideas in previous stages. In particular, this stage was also considered to provide specific conditions together to support novice designers' learning of appropriate ideation strategies based on literature. The majority of novice designers tend to deal with collected information and ideas on the same level, while experienced designers sort out important issues then concentrate on specifics (Ho, 2001). Novice designers also tend to ignore difficult issues when they cannot easily overcome the problem (Dinar et al., 2015). In this context, two conditions are given. Firstly, users need to review generated ideas in the previous three stages before starting the Final concept stage as they can implement generated ideas into the final solution. Secondly, users can generate only one final solution. These guideline support to improve designers' solution concept generation abilities in response to the their insufficient ideation process and activities (Dinar et al., 2015; Ho, 2001).

The fifth stage of the KEDIM template is the Design object step. It is an extra part compared to the four stages within SECI, because ideation requires considering the design object in parallel. The Design object step support users' parallel ideation with a set of specific ideation themes and the design object together. In this light, the Design object section requires sketching of the basic and simple form of the design object (Figure 5.5 a to b). Compared to users implementation of specific ideation stages 1 to 4, the design object for sketching can be provided by users, or the organiser (teacher, team leader or others) according to purpose (classes, individual or group work, and others) or situation (the number of participants, time resource, and others). Different guidelines are required. In the case of the user, they need to draw basic and simple forms of the design object given before or during the Motif section (1st stage). In cases where the organiser provides the design object form, care must be taken to ensure it works as a given external resource closely relating the represented desired goals in the design brief as well as participants' ideation abilities. It means the organiser needs to sketch the design object form to reflect the essentials of the desired goals in the design brief, but also to prevent issues that can cause users' fixations or bias. For instance, basic and simple representations of the design object describing detailed form or specifics can cause users' fixations or bias. On the other hand, insufficient information can increase confusion.

On the contrary to these precautions, it could be an effective medium to link the design brief and users by increasing stimulation. If a specific issue was given in the design brief, such as exploration of novel leg forms, the organiser can skip this part (Figure 5.5.c). The visual marks can increase users' motivation and stimulation through intuitive delivery of the key desired goal. With respect to it working as an external resource, users are able to consider a variation of elements (form of legs and their combination, the number of legs, materials, and others) in order to draw the specific part of the object. When a basic and simple form of the design object is given with detailed description, users can implement ideation in an unrestricted environment and mitigate fixations.

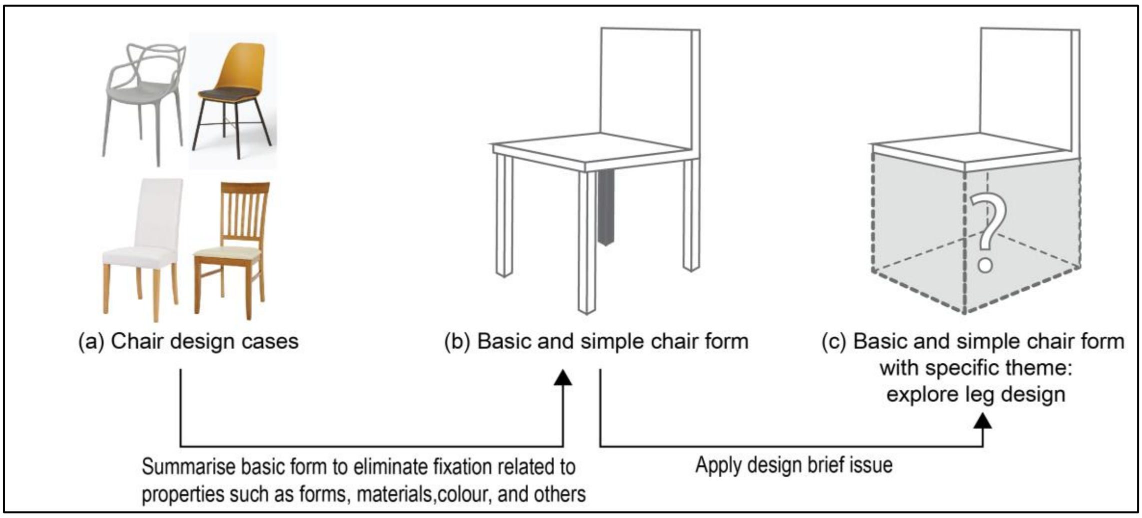


Figure 5.5 Conversion process from diverse design cases to basic and simple form for Design object section along with chair example (source for (a) from top-left moving in a clockwise direction: Philippe Starck's Kartell Masters Chair, John Lewis & Partners' Whistler Dining Chair, Alba Slat Back Dining Chair, and Lydia Leather Effect Dining Chair)

5.5 Method of use for Systematic Brainstorming

The SBI template consists of two parts with five specific stages. The first part is the four sequential ideation stages along with the overall ideation process (Motif, Specific part of design object, Whole part of design object, and final concept). The second part is the Design object section, which acts as a consistent reminder about the design object given during ideation.

Overall, the first stage in a given cycle involves populating the 'motifs' box (in the top-left corner of the SBI template) with the motifs (elements of an image or design) that have been chosen as inspiration. Having done this, the user proceeds through the sections in a clockwise direction. The top left-hand box in the SBI template is where the motif(s) is explored and then in the top right-hand box the motif(s) can be applied to particular parts of the design object. In the bottom right-hand corner of the template, these applications of the motif are integrated into the whole design as candidate design solutions, and finally this is developed into a final design concept in the bottom left-hand corner of the template. During ideation through these four stages, design objects (the central part on the template) are considered in parallel, with marks of important findings or ideas.

In the aforementioned method of usage, criterion for completion of each section need to be defined to provide clear instruction for users, in order to increase users concentration and stimulation based on ease of use of method. The completion criteria need to be flexibly suggested, with respect of ideation including diverse variations (allowed time, the number and tendency of participants, design brief, and others). For instance, the following examples can be given; filling each section, user's satisfaction, time, and others.

5.6 Method of Expression

Expression of designers thought is a core part of ideation performance. These re-interpretations are mainly implemented through text, writing, and both together. Their appropriate use is required according to the situation as discussed in Section 2.3. Firstly, sketching can be used to illustrate visible (motif, design cases, ideas generated, and others) and also invisible sources (phenomena, situation, individual experience, data from interview or observation, and others).

Secondly, text can be used for two objectives. Text notes can be used to describe, enhance or elaborate sketching, which can be controlled by skill level or given situation (time, tools, or others). There are limitations associated with illustrations such as representing a high degree of complexity or seamless forms, invisible issues (concerning the situation, or individual experience), or atypical conceptual motif (specific properties of design motif, or atypical phenomenon such as fog or haze). These difficulties frequently arise in the ideation process during the exploration of specific forms from concepts. In response to this issue, text can provide detail or extra description. What is more, text expression can be used to immediately note difficult issues that users face. Novice designers tend to ignore problems that they cannot handle (Dinar et al., 2015), but notes can help to consistently remind and prevent avoidance thus bringing these issues to the fore in ideation.

5.7 Summary

This chapter introduced Systematic Brainstorming (SBI). Brainstorming is a general ideation method to support free idea generation with mitigation of fixations. On the other hand, these properties cause some confusion and heavily rely on individual abilities for solution generation. In response to these limitations, SBI provides systematic idea generation process based on a basic brainstorming concept. As a result, a paper template was developed with guidelines and the SBI method was employed to enhance required goals; systematic ideation process from obtained analogies and moving from information to novel solutions. The majority of novice designers demonstrate ineffective strategies and activities during ideation, compared to experienced designers (see Table 2.2). They tend to 1) ignore the difficult issues that they cannot handle (Dinar et al., 2015), and 2) process collected information or ideas on the same level (Ho, 2001). In response to these limitations, SBI supports novice designers' abilities to generate solution concepts.

Chapter 6 – Results from evaluations of KEDIM

The evaluation experiments generated data for evaluation of the proposed method and defining further required revision issues based on predicted outcomes. According to the Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009), the design of the evaluation experiment should consider the collection of various perspectives of assessment data. Analysis of the obtained data provides assessment of a method developed with respect of desired goals identified in the Research Clarification stage. It also enables identification of unexpected issues and further requirements.

This chapter provides detailed information on the experiments carried out to evaluate KEDIM. Beginning with an explanation of group and individual work completed in Section 6.2.1, and 6.2.2, the status of collected evaluation data and its classification (specification or combining) to extract detailed assessment data is reported in Section 6.2.3, and 6.2.4. These obtained data were analysed to evaluate KEDIM and the three parts of KEDIM (DOS, PMGS, and SBI) in Section 6.3. This assessment identified requirements and unexpected events for further development issues. Chapter 6 closes with a summary of the KEDIM evaluation in Section 6.4.

6.1 Evaluation experiments, and data collection from experiments

The evaluation experiments for KEDIM were designed to collect various assessment data from the expected users and environment in Research Clarification (Figure 3.3). Experiments by researcher and participants were carried out in order to collect the appropriate evaluation data with respect of the properties of the three tools of KEDIM. For assessment of the first and second stages of KEDIM, the Database of Design Cases (DOS) and Perceptual Mapping Generation Software (PMGS), the data from experiments predominantly by the researcher was analysed because population of a large database is time consuming, and understanding is required to make and understand outcomes from PMGS. For evaluation of the third stage of KEDIM, Systematic Brainstorming (SBI), the data from workshops with participants was chiefly reviewed, because brainstorming is a common idea generation tool, but a drawback, especially for novice designers, lies in findings inspiration to drive the design ideation process and the lack of a defined process for design ideation. Aside from this, observation and discussion notes by the researcher, and questionnaires completed by participants were analysed for the three tools that comprise KEDIM – Database of Design Cases (DOS), Perceptual Mapping Generation Software (PMGS), and Systematic Brainstorming (SBI).

The evaluation data from the experiments focused on recording issues identified findings and experience in order to assess the Database for case study – how well it supports understanding of a large volume of design cases during the population and reviewing process. In particular, tracking the number of corrections on the populated database (Figure 6.11) demonstrated that the researcher acquired the accurate information of design cases with very low percentage of corrections as 0.6% (47 of 7,560 pieces of data).

For the Perceptual Mapping Generation Software, three groups of perceptual mapping outcomes (30 cases and 180 cases using Adobe's Illustrator, and 540 cases using PMGS) were made by the researcher in order to collect comparison data to 1) determine working time and the amount of information delivered per case, and 2) analyse the making experience and process along with drawing analogies. Analysis of the Database for case study and PMGS will be provided in Section 6.3.

6.2 Data collection from experiments with participants

Experiments were carried out with 101 design department students in the United Kingdom and South Korea (Table 6.1), in order to collect the evaluation data of KEDIM, and focus on Systematic Brainstorming (SBI).

Table 6.1 Status of completed experiments with participants

<table>
<tr><th colspan="2">Experiments ID</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th colspan="2">Location</th><th colspan="3">South Korea</th><th>United Kingdom</th></tr>
<tr><th colspan="2">Date and Hours</th><th>27.09.2017
4 hours</th><th>28.09.2017
4 hours</th><th>29.09.2017
2 hours</th><th>22.10.2018
1.5 hours</th></tr>
<tr><td rowspan="5">Group experiment (the number of participants)</td><td>DOS</td><td rowspan="3">27</td><td rowspan="3">34</td><td></td><td></td></tr>
<tr><td>PMGS</td><td></td><td></td></tr>
<tr><td>SBI</td><td>10</td><td>30</td></tr>
<tr><td rowspan="2">Total</td><td colspan="3">71</td><td>30</td></tr>
<tr><td colspan="4">101</td></tr>
<tr><td rowspan="2">Individual experiment (the number of participants)</td><td>SBI</td><td></td><td>1</td><td></td><td></td></tr>
<tr><td>Total</td><td colspan="4">1</td></tr>
</table>

Group and individual work was carried out in order to obtain assessment data within two different ideation environments. Group work aimed to collect a high volume of data from diverse participants. Compared to this, individual work focused on collecting data from intensive usage of KEDIM for a long period, including in-depth observation and discussion. The detailed contexts of group and individual work are provided in the following subsections 6.2.1, and 6.2.2.

Experiments were carried out in two countries (United Kingdom, and South Korea) to collect data from multiple participants possessing diverse cultural and educational backgrounds which related to the ideation abilities of novice designers. Experiments in multiple countries need to consider language issues. The given information (presentation, guidelines, instructions, questionnaire, and the SBI template) contained the same context for the Korean and British experiments, although the wording of some questions was adjusted to take into account cultural differences. Participants used their own language (mother tongue) during the workshops. The collected data from the South Korean workshops was translated into English, and it is noted when a translated context is used.

The design of the evaluation experiments and relevant issues (participant consent, materials, data protection and others) was approved by the ethical committee of the University of Leeds (Reference number: MEEC 17-003 and MEEC 17-026), and experiments were conducted according to the plan designed.

6.2.1 Group work

Group work was implemented to obtain a high volume of assessment data and feedback on KEDIM according to the research design structure (Table 3.2). Four experiments with 101 design students in the United Kingdom and South Korea were conducted (Figure 6.1). The general number in groups is commonly between 6 to 12 (McLafferty, 2004; Rabiee, 2004), and in these group experiments the teams consisted of around 6 members for practical ideation group work.

Figure 6.1 Group work

Group workshops started with a presentation to explain general information: research background, goals, workshop plan, and participants' rights. After that, the required information for the workshop was informed. Biologically inspired design cases were presented according to used manufacturing technologies (handcraft, mass-production, and additive manufacturing technology). It aimed to stimulate participants and bring forth relevant information, experience, and ideas for supporting an effective ideation workshop to be conducted under limited time (Goldschmidt and Smolkov, 2006). Despite the showing of case images increasing stimulation (Knoll and Horton, 2011), it can also have latent negative impacts causing fixations as it is an obstacle for creative ideation (Moreno et al., 2015; Vasconcelos et al., 2017). To overcome this predictable limited variation, three pieces of information for each case (motif, design result, and ideation properties) were shown together for five seconds. For instance, Figure 6.2 is one of the slides which was used during the presentation, and it shows three pieces of ideation information (motif, ideation process by software, and design result) for Joris Laarman's bone chair (2006). Prior to showing the design cases, the following instruction was given: 'assume the ideation process based on the given information for stimulation, and avoid focussing on only the design result to prevent occurrence of fixations'. Regarding this fixation issue, the final ideation outcomes in brainstorming were classified depending on the similarity of given design cases in order to review the degree of fixation from exposed cases in Section 6.3. Once the design cases had been shown, the objectives of KEDIM, the method of use, the design brief (Section 3.2.7), and relevant ideation instruction (method of expression in Section 5.6) were provided.

Figure 6.2 Example of design cases slide from the presentation. Joris Laarman's bone chair (2006)

Once the presentation was completed, participants used KEDIM for evaluation. Three parts of KEDIM (DOS, PMGS, and SBI) were selectively used according to the allocated time for each experiment. DOS and PMGS were optionally evaluated in case enough time (4 hours) was given, and carried out before using SBI. The DOS outcome (biologically inspired design database version 2.1 in Section 4.1), and PMGS outcomes (ten versions of perceptual mappings based on the DOS outcomes) were provided through hard copy (Figure 6.3) and digital files (PDF format) for appraisal by participants. Then, the DOS outcome and PMGS were provided so that participants could use on computer. Experiment 1 and 2 (61 of 101 participants, Table 6.1) used and reviewed all three tools of KEDIM, and evaluated their effectiveness, ease of use, and likelihood of future use through questionnaire.

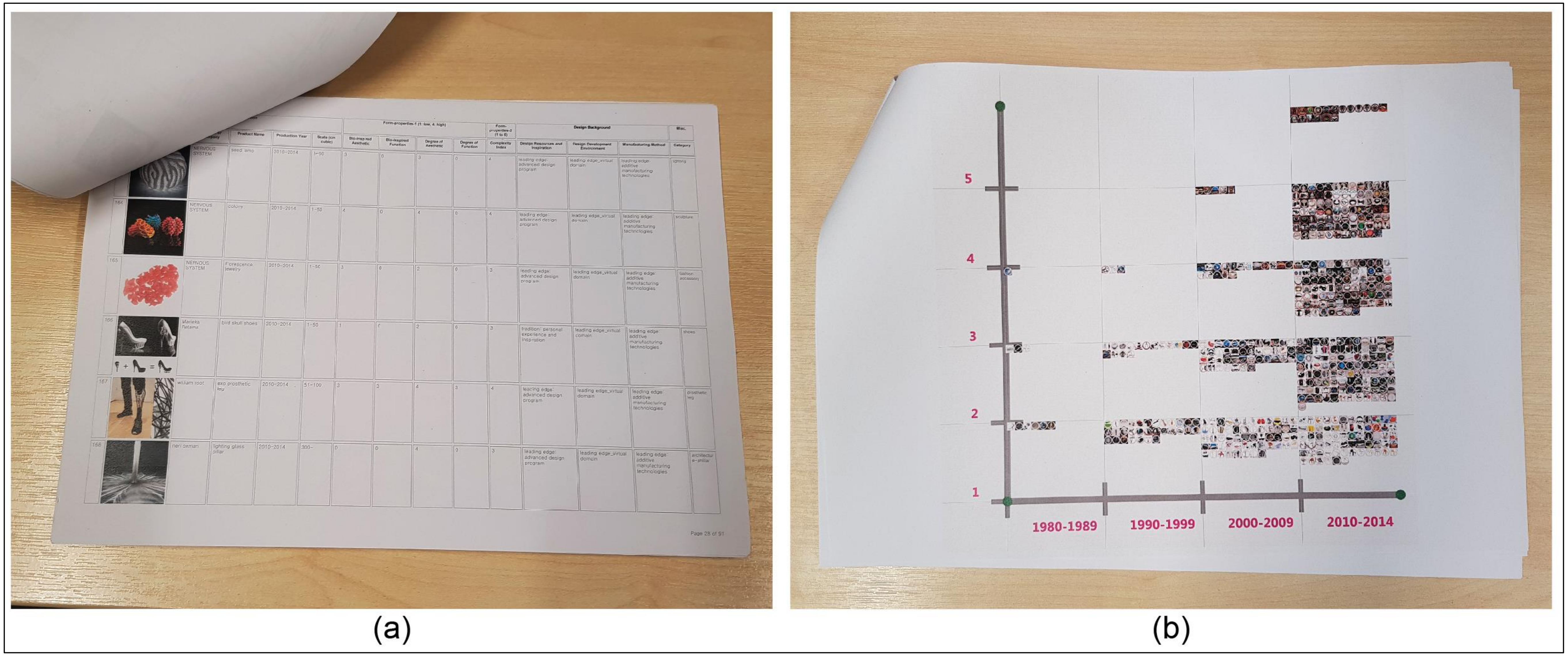
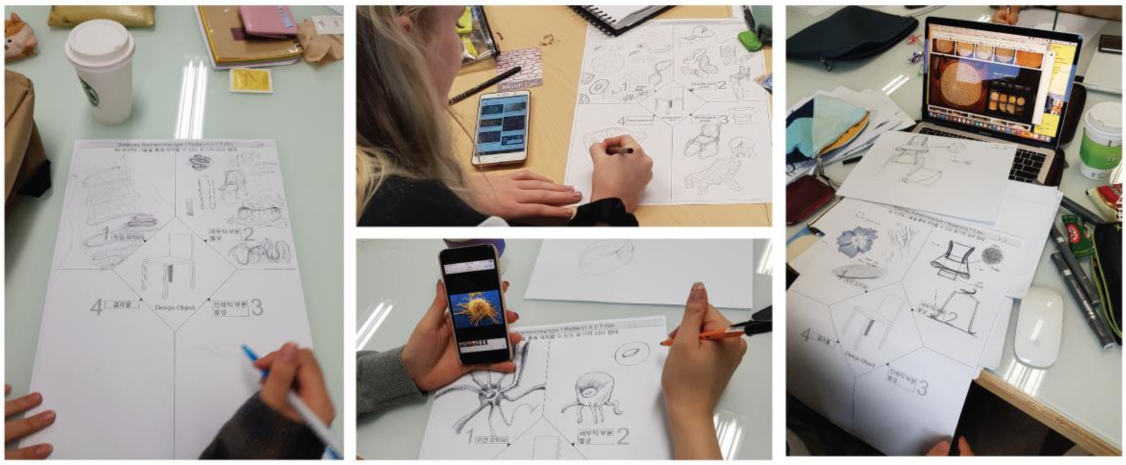


Figure 6.3 Output of DOS and PMGS. (a) biologically inspired design database version 2.1 (A4 size), and (b) Perceptual Mapping Generation Software outcomes from (a) (A3 size)

Brainstorming evaluation using SBI or blank paper was compulsorily carried out, because of it having the benefit that it can produce diverse perspectives of data (sketching outcomes, observation, and discussion) in response to the desired situation and goals of KEDIM. The obtained data is also noteworthy as it involves the participants' actions and activities along with ideation development from the design brief given to the final solution concept outcome. Brainstorming workshops were carried out to derive data for comparative analysis (Table 6.2). Independent variation was the paper template for brainstorming: SBI for the experimental group, and blank paper for the control group. For the experimental group, SBI was given with the general and simple form of a chair for the design object section (Figure 6.5). The guideline for SBI was instructed: progress through specific ideation sections in order for 15 minutes each, and the researcher informed participants every 15 minutes. At the fourth stage (final concept design) it was necessary to ideate the final outcome along with ideas generated in previous stages. On the other hand, control groups ideating freely were only required to generate one final ideation outcome. During the workshop, participants could talk with other colleagues or researchers, and use mobile phones and laptops (Figure 6.4).

Table 6.2 Experimental research design for comparative analysis of SBI

Variations (V)		Experimental group	Control group
Control V	**Participant background (age, education environment, working experience)**	Similar	
	Experiment design (instruction, design brief, materials, topic, time plan, and others)	Same	
Independent V	**Paper style for brainstorming ideation**	SBI (Suggested way)	Blank Paper (Conventional way)



(a) focus on re-interpretation (b) ideation with mobile phone (c) ideation with laptop

Figure 6.4 Group work: experiments according to use of tools

The same design brief was given to the experimental and control groups. In general, ideation workshops provide one or two design briefs about the design object, background, manufacturing technologies or situation (Dorst and Cross, 2001; Anderson, 2012; El-Zanfaly, 2015). However, this was omitted as it was viewed as likely to cause confusion amongst participants in these experiments because the provision of specific design brief(s) restricts actions involving searching, decision-making, and idea generation with respect of limited experiment time (1.5 to 4 hours). In this light, these experiments gave three conceptual design briefs that provide clear ideation instruction, but can derive various results whilst decreasing confusion. These design briefs also include the required considerations (design object, motifs, and manufacturing technologies) in actual practical design fields as below.

- Topic: Design your own chair that satisfies the following themes:
- Motivation: Biologically inspired resources
- Making: Additive manufacturing technology (3D printer)

A detailed explanation of the design brief was informed providing relative materials. Firstly, four motifs from nature were given (Korea: Cell, Water, Twig, and Skeleton, UK: Cell and Water), and each team selected one motif by selecting a card with the motif’s image. The four motifs represent a conceptual model which participants can expand in various ways. For instance, water can be interpreted as; the flow of water, ice, fog, and waves. Ideation processes starting from natural motifs allow understanding of participants’ activities through analysing reverse tracking of empirical data. Secondly, using a chair as the design object was beneficial as it is a familiar object to participants. Regarding the SBI template, the general and simple form of a chair was given by the researcher (Figure 6.5). The given form was for reference, and participants can change any elements and parts, except the essential functionality as a seat. Thirdly, participants ideate their chair to be produced using additive manufacturing technologies. This manufacturing technology emerged in current conceptual design cases during analysis of biologically inspired design database version 2.1. The major challenge for designers was to use the potential of additive manufacturing technologies (manufacturing complex and seamless forms) and mitigate fixations (conventional experience and learning) (Anthoniw, 2013). Short videos showing the working process and properties of additive manufacturing technologies were shown to increase participants' understanding. Once the aforementioned design briefs had been introduced, participants started their use of KEDIM.

A questionnaire was necessary to ask about individual ideation background, and obtain assessment data and feedback, once use of KEDIM was complete. The questionnaire consists of two parts. The first part deals with the participants' individual ideation background in response to the design brief (where they obtained information and which method they used to develop their solution), and asked about the real conditions and difficulties they faced when applying emerging technologies into ideation. The second part focused on assessment of KEDIM along with its level of effectiveness, difficulty to use, and how often they might use it in future work. The questionnaire contained the same questions for the Korean (Figure 6.6) and UK experiments (Figure 6.7), although the wording of some questions was adjusted to take into account cultural differences. For the UK experimental group, one question was added to ask regarding the effectiveness of SBI compared to blank paper (Question ID 35 in Figure 6.7). The United Kingdom and Korean groups response was through online survey (Jisc's online survey. https://www.onlinesurveys.ac.uk), and hard copy respectively.

In summary, group work was completed with 101 design department students in the United Kingdom and South Korea, with the aim of collecting a high number of varied perspectives and evaluation data for KEDIM in response to the desired situation with considered environments and user groups - sketching outcome, questionnaire, observation, and discussion. The assessment data implies some limitations from the properties of group work: implementation with many participants all together within a limited time (1.5 to 4 hours). It did not produce the required data after use for a long period, and was difficult for in-depth discussion or observation. In the case of brainstorming evaluation, each group used only one paper template (SBI or blank paper), not both versions together. Individual work was carried out to collect the required assessment data, and detailed contexts are provided in Section 6.2.2.

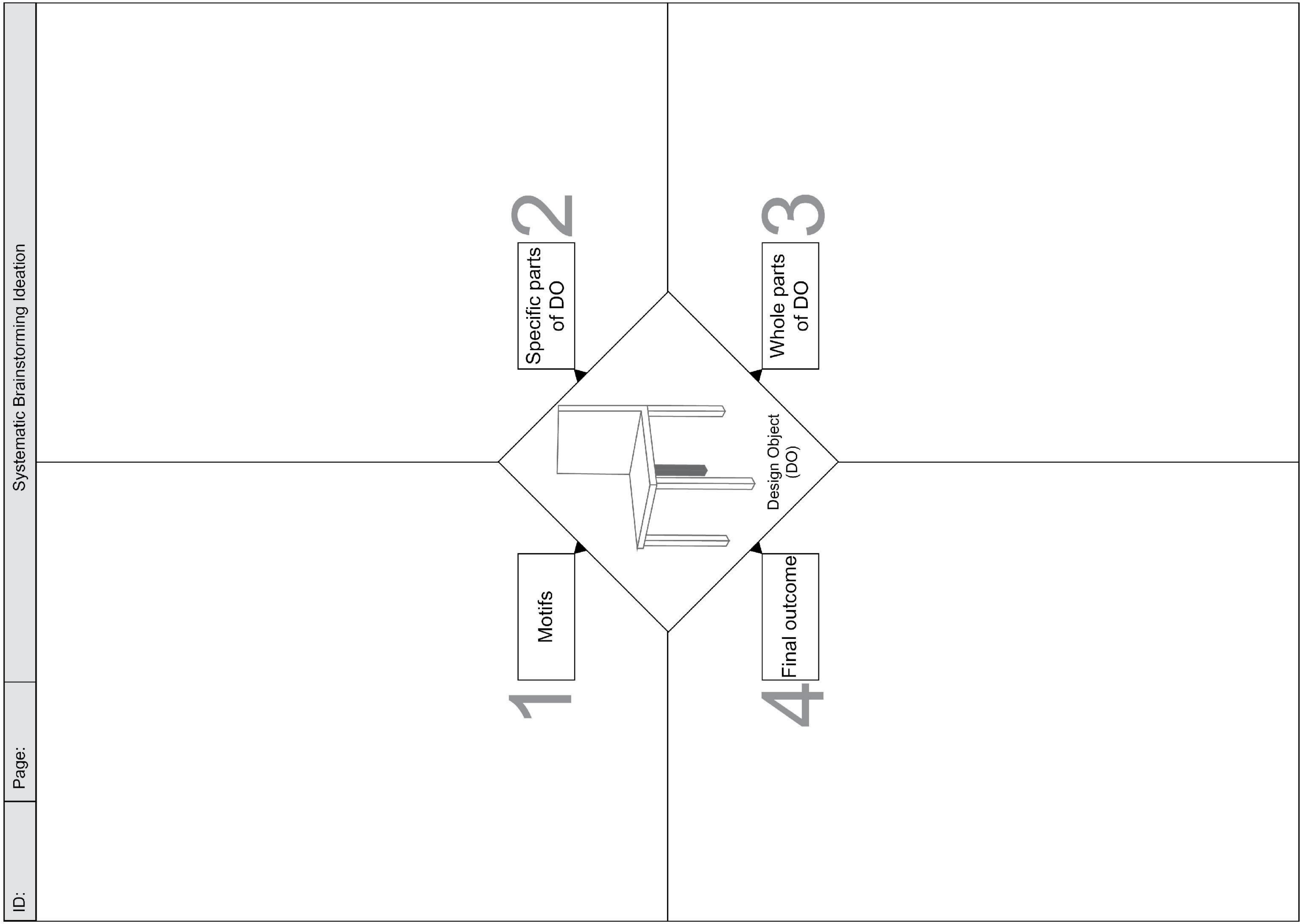


Figure 6.5 Systematic Brainstorming Ideation template for biologically inspired chair design

ID	Questionnaire - Korean workshop	0: Non-applicable, 1: definitely no, 2: no, 3: normal, 4: yes, 5: definitely yes.					
		0	1	2	3	4	5
	Topic 1: Participant's ideation background						
1	Have you frequently experienced forced revisions to the design process from design concept to the final outcome due to external factors (please see question 1.2 in the list)?		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
2	How much is the degree of the forced revisions due to external factors?		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
	In relation to question 1 and 1.1, please evaluate the level of impact on each of the following design stages due to the forced revisions caused by the external factors? (0: not applicable, 1: almost none 5: very negative)						
3	-Sketch.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
4	-Modelling.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
5	-Rendering.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
6	-Mock-up.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
7	-Preparation for production.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
8	In relation to question 1.2, do you think 3D printing technology (additive manufacturing technology) can negate the forced revisions caused by the external factors?		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
9	In relation to question 1.3, what stage/s in question 1.2 do you think 3D printing technology will prove most effective? (short-answer question, multi-selection available)	**(short answer question)**					
10	Do you think that design development environment and outcomes have a close relationship?		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
11	Do you have an interest in using 3D printing technology in the design process or ideation?		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
12	Do you have experience of using 3D printing technology in the design process or ideation?		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
13	If you answered yes in question 2.2, how effective did it prove?		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
14	In relation to question 2.3, could you please briefly note the experienced limitations or bene	**(short answer question)**					
15	Please evaluate the potential of 3D printing technologies in perspective of designers in the ideation stages.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
16	Could you please briefly note the reason(s) for your selection in question 2.5?	**(short answer question)**					
	Topic 2.1: Workshop Review (Database for design cases, and Perceptual mapping generation software)						
17	Please evaluate the effectiveness.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
18	Please evaluate the potential.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
19	Do you have an interest to use it in further works?		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
20	How difficult was it to use? (1: the most easy, 5: the most difficult)		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
	Topic 2.2: Workshop Review (Brainstorming: Blank paper or Systematic Brainstorming Ideation)						
21	Please evaluate the effectiveness.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
22	Please evaluate the potential.		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
23	Do you have an interest to use it in further works?		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
24	How difficult was it to use? (1: the most easy, 5: the most difficult)		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
	Topic 5: Feedbacks						
25		**(short answer question)**					

Figure 6.6 Questionnaire - Korean Experiments (translate version from Korean to English language)

Questionnaire - UK workshop								
ID	Questions		0: Non-applicable, 1: definitely no, 2: no, 3: normal, 4: yes, 5: definitely yes.					
			0	1	2	3	4	5
Topic 1: Participant's ideation background								
1	**Your Information/Inspiration Sources:** How often do you use the following sources to obtain information for ideation?	Books		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
2		Journal		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
3		Internet website (google, pinterest, youtube, and others)		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
4		Personal memory or experience		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
5		Please describe any further source(s) not described above	(short answer question)					
6		What are your prefered online source(s) for collecting information (e.g. Google, Pinterest, Youtube, and other site)?	(short answer question)					
7	**Your Preferred Information Type:** How often do you use the following types of information for ideation?	Text format		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
8		Image format		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
9		Video format		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
10		Personal memory or experience		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
11		Please describe any other type(s) of information not described above.	(short answer question)					
12		Please briefly describe the reasons for your *most often* and *least often* used types of information (advantages and limitations).	(short answer question)					
13	**Your Preferred Progression Method:** Once you have gathered information/inspiration, how useful do you find the following methods to dvelop your ideas?	Note method		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
14		Sketch method		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
15		Case study method		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
16		Perceptual mapping method		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
17	**How frequently do you use the following methods to realise your ideas?**	Sketch (brainstorming, thumbnail sketch, and others)		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
18		Modeling (Solidworks, Rhino 3D, 3D Max, AutoCad, and others)		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
19		Rendering (Photoshop, Keyshots, and others)		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
20		Mock-up (Manufacture physical object/s)		1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
21	**Please evaluate how useful you find the following methods in realising your ideas.**	Sketch (brainstorming, thumbnail sketch, and others)		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
22		Modeling (Solidworks, Rhino 3D, 3D Max, AutoCad, and others)		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
23		Rendering (Photoshop, Keyshots, and others)		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
24		Mock-up (Manufacture physical object/s)		1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
25	**Overall, how valuable do you find methods in developing your thinking?**			1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
26	**Please briefly describe any challenges or limitations you faced using these methods.**		(short answer question)					
27	**If there are any other method(s) you use that are not listed above please describe them here alongside a ranking of how useful you find the method.**		(short answer question)					
Topic 2: Workshop Review								
28	How often have you used new technologies within the ideation process to realise you ideas? (e.g. additive manufacturing technology (3D printing))			1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
29	How difficult have you found using and integrating new technologies into the ideation process?		0 Not applicable	1 Extremly difficult	2 Challenging	3 Moderate Difficulty	4 Relatively Easy	5 Very Easy
30	Please briefly describe any challenges you have experienced.		(short answer question)					
Topic 3: Workshop Review 2								
31	Please select which ideation method you used during the workshop.		Blank template	Systematic Brainstorming Ideation template				
32	Please evaluate the effectiveness of the ideation method.			1 Extremely Ineffective	2 Little Efectiveness	3 Moderately Effective	4 Effective	5 High Effective
33	How often might you use this method in your future work?			1 Never	2 Rarely	3 Sometimes	4 Often	5 Very Often
34	How difficult did you find this method to use?			1 Extremly difficult	2 Challenging	3 Moderate Difficulty	4 Relatively Easy	5 Very Easy
35	(Experimental group only)How useful did you find the SBI template compared to the previous methods/techniques you have used for brainstorming?		0 Not applicable	1 Not useful at all	2 Slightly useful	3 Moderatley useful	4 Very useful	5 Extremely useful
Topic 4: Feedbacks								
36	Please use this space to provide any feedback you wish to leave on this workshop.		(short answer question)					

Figure 6.7 Questionnaire – the United Kingdom Experiments

6.2.2 Individual work

Individual work was conducted with the aim of obtaining assessment data on Systematic Brainstorming (SBI) for a long period, and during in-depth discussion and observation. One participant was selected from the group work applicants by reviewing their availability period and brainstorming outcomes in group work.

A detailed plan of individual work was established with respect to the participant's situation and preference. As a result of discussion, the participant focussed on brainstorming with the same theme of a biologically inspired chair based on additive manufacturing technologies. Over 8 weeks, the participant conducted brainstorming one or two day/s per week. For the first 4 weeks, the participant used SBI and blank paper alternatively as a fixed order for learning, and took a rest for 1 week. After that, the participant could use any paper template according to their preference for the next 4 weeks based on previous leaning. The data collected contained information that the participant could learn and use (SBI and blank paper together) according to various situations for a long period (8 weeks) with in-depth observation and discussion. A detailed assessment of SBI and blank paper was provided, and it also suggests guidelines for their use together according to various situations.

The remote individual experiment was carried out because of the different location of the participant and researcher (South Korea and the United Kingdom). Regarding collecting data from each brainstorming session, video recording was used for observation of the process (Figure 6.8), and self-report was written by the participant at the end of each session. The generated information (video recording, self-report, and sketching outcomes) was sent once a week for regular discussion through remote meeting. The discussion dealt with feedback, suggestions, and any detailed issues, and the agendas were recorded by the researcher.

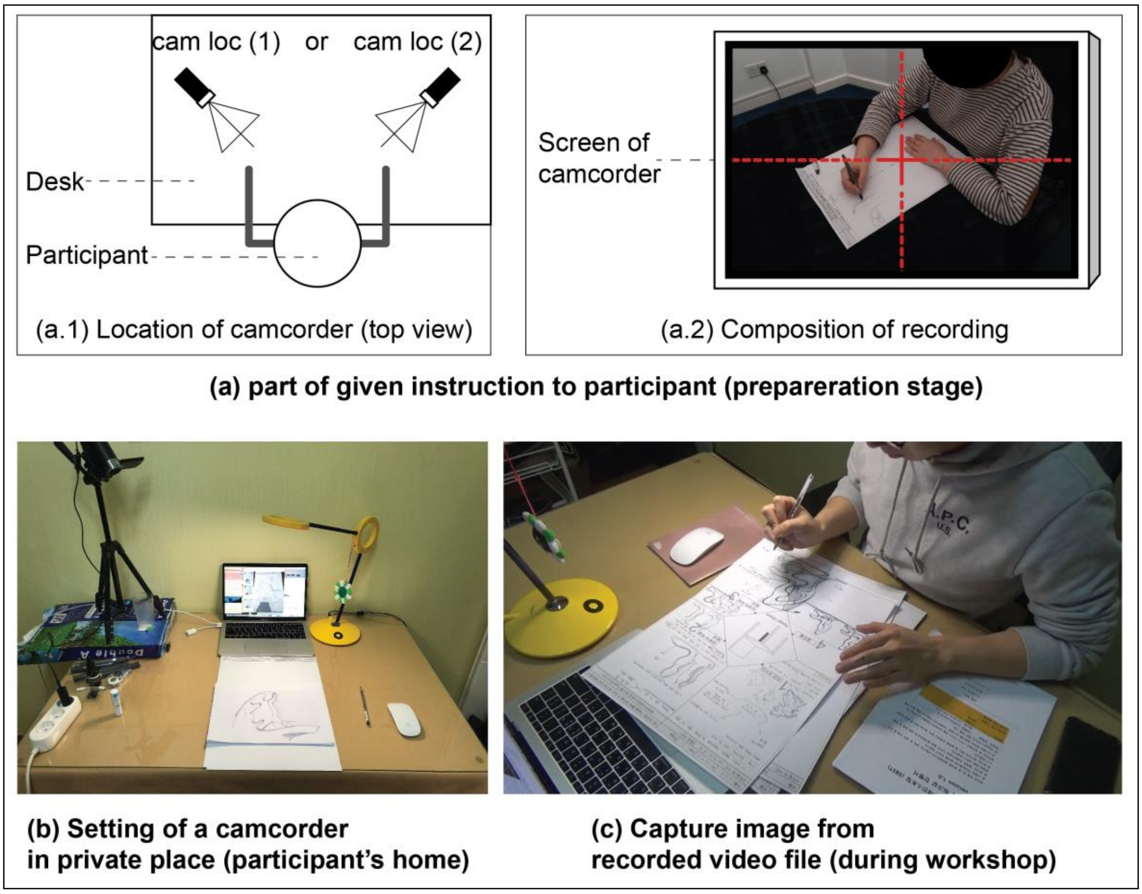


Figure 6.8 Observation of brainstorming ideation through video recording for individual work

6.2.3 Raw data collection

Evaluation experiments were completed by the researcher and participants (group and individual work). A total of six data types were collected – description from workshop by researcher (1 in Table 6.3), and sketching outcomes, questionnaire, observation and discussion notes, and self-report from workshop with participants (2 in Table 6.3). Each type involves raw data for evaluation of each tool or the whole of KEDIM with respect of user perception or derived outcomes. Table 6.3 provides detailed information of collected data according to assessment targets with a short explanation.

Table 6.3 Overview of collected raw data

1. Collected data status from experiments by researcher							
1.1. Description during the usage of DOS and PMGS - for evaluation of DOS and PMGS							
Statement by researcher that record findings and experience during the usage of DOS and PMGS							
2. Collected data status from experiments by participant							
Experiment types	**Group work**					**Individual work**	
	Experimental groups			**Control groups**		**Both**	
Experiment ID (location)	**1 (SK: South Korea)**	**2 (SK)**	**4 (UK)**	**3 (SK)**	**4 (UK)**	**Selected from 2**	
The number of participants	27	34	16	10	14	1	
Total	77			24		1	
	101					1	
2.1. Sketching outcome - for evaluation of SBI							
The number of pieces of paper collected	31	34	16	10	14	11	7
Total	81			34		18	
	115 (1.1 papers per participant)					18	
2.2. Questionnaire – for evaluation of user perception about effectiveness, ease of use, and likelihood of future use about DOS, PMGS, and SBI							
The number of questionnaires	27	33	12	10	14	1	
Total	72			24		1	
	96 (95% of participants)					1	
2.3. Observation – for evaluation of DOS, PMGS, and SBI							
	Recording notes by researcher during workshops					Video recording	
2.4. Discussion – for evaluation of DOS, PMGS, and SBI							
	Recording notes through informal conversation with participants during workshops					Regular remote videophone by Skype (once per a week)	
2.5. Self-report – for evaluation of SBI							
The number of self-reports	(not required)					1	

The collected data from a high number of participants had limitations for in-depth appraisal with respect of variety, type, and amount of data. For instance, sketching outcomes imply multiple information, and some data (observation, discussion, and self-report) formed with description of diverse issues. These issues were linked to the requirement of their classification in order to aid detailed understanding and assessment. The explanation of the classification of collected raw data is described in the following section.

6.2.4 Handling of raw data collected for KEDIM assessment

The six types of raw data collected from the experiments were classified in order to assess parts of KEDIM (DOS, PMGS, and SBI) with respect to the desired goals and situation. Figure 6.9 illustrates this two phase data collection process. For assessment of the three tools of KEDIM, 1) statistical analysis, and 2) extracting key issues from notes, short answer of questionnaire, and observation and discussion notes was carried out. Answers to multiple choice questions within the questionnaire were shown as percentages according to the degree of questions which asked about user perception of ease of use, effectiveness, and likelihood of future use. Extraction of key issues were implemented from data involving atypical descriptive information (description by researcher, short answers in the questionnaire, notes from observation and discussion). Identified key issues were then classified according to similar themes to recognise common, specific, and unexpected issues.

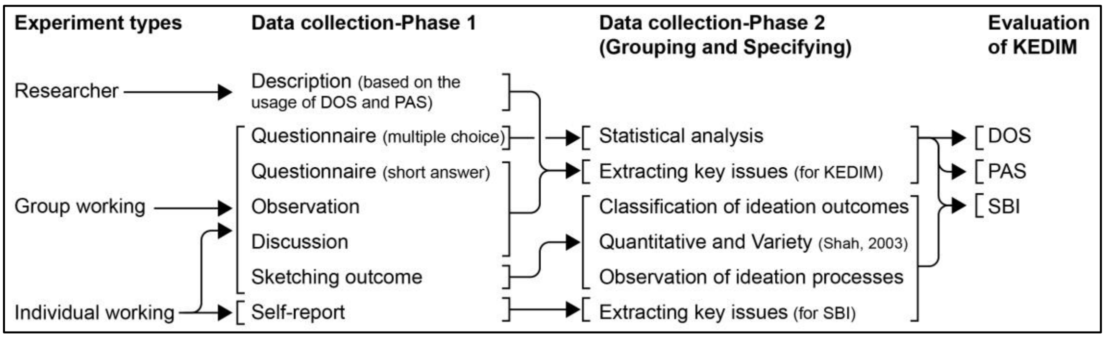


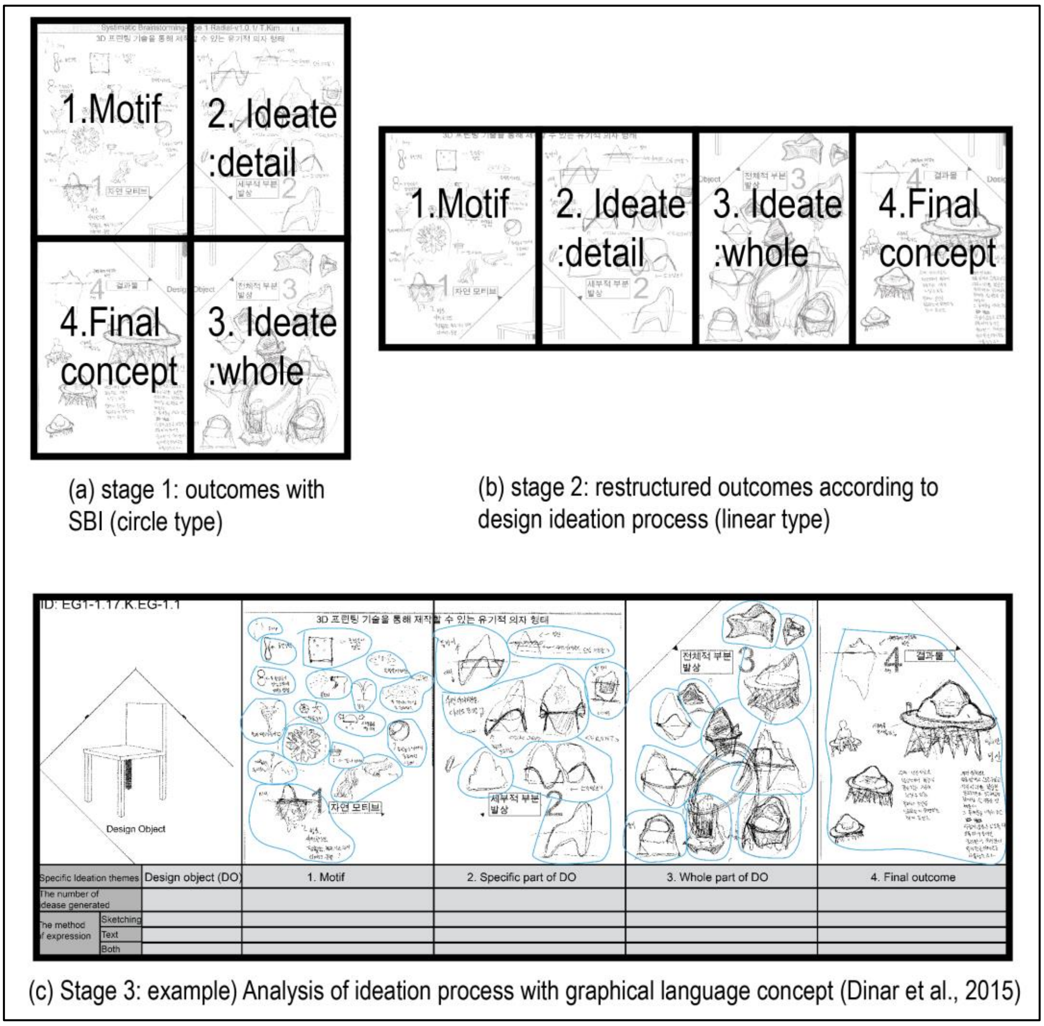
Figure 6.9 Structure of data collection from experiments

In particular, the detailed analysis of SBI was conducted based on appraisal of participants' activities by comparison of the sketching outcomes and self-reporting. Sketching outcomes implying comprehensive ideation data were appraised to analyse or assume participants' activities, and reaction according to faced situations along with searching, selection, and interpretation of information and ideas. The obtained data was used for comparative analysis between conventional brainstorming (using blank paper) and SBI. Restructuring of sketching outcomes from circle to linear style was carried out in order to analyse and show results according to an analysis process designed to increase presentation along with the ideation process (Figure 6.10.a, and b). Three analyses were implemented as below.

- Quantitative and variety of ideas generated based on the measurement matrix of ideation effectiveness (Shah, 2003): the number of ideas generated (interpreted information by users), and their variety was counted and calculated to assess the effectiveness of the ideation process.

- Analysis of the ideation process: correlation of interpreted information (generated motifs and ideas) was traced from final concept (section 4) to motifs (section 1) with graphical language concept (Dinar et al., 2015), in order to assume participants' ideation activities. Method of expression (sketching, text, and both) was also appraised to ensure that participants are using appropriate strategies according to the situation or desired goals (Figure 6.10.c).

- Classification of final concept outcomes: the final ideation results from participants were classified according to three degrees of similarity (very similar, somewhat similar, and different) compared to the design cases shown in the presentation. This classification was carried out for assessment of how well participants mitigate fixations between the experiment and control groups.



(a) stage 1: outcomes with SBI (circle type)

(b) stage 2: restructured outcomes according to design ideation process (linear type)

(c) Stage 3: example) Analysis of ideation process with graphical language concept (Dinar et al., 2015)

Figure 6.10 Process for ideation analysis

In summary, assessment data for KEDIM was acquired by the researcher, from participants in response to the Research Clarification, based on evaluation experiments. The collected six raw data type capturing experiments (description by researcher, observation, discussion, and self-report) and outcomes (questionnaires, and sketching outcomes) were classified with the aim of collecting appropriate data for analysis of each tool of KEDIM. In the following section, detailed context of KEDIM evaluation is given followed by assessment, further revision issues, and unexpected events.

6.3 Analysis of evaluation experiments

The six types of collected data were analysed in order to assess each of the three parts of KEDIM (Database of Design Cases (DOS), Perceptual Mapping Generation Software (PMGS), and Systematic Brainstorming (SBI)) in order to review how well they achieve the desired goals and situation, and define further development issues based on identified limitations. These assessments were drawn together in order to assess KEDIM and its further developments issues based on limitations.

6.3.1 Database of Design Cases

Database of Design Cases (DOS) (first stage of KEDIM) was developed with the aim of enhancing learning through design cases with improved cognition in response to the identified current limitation (understanding partial case information).

Assessment of DOS focused on the achievement of desired goals during population, and three types of data were analysed – 1) extracting key issues from researcher's description during the population of the biologically inspired design database version 2.4 (7,560 elements: 540 cases, with 14 elements per case according to Table 4.1. Figure 4.3 and 4.4 showing part of outcomes), 2) Cohen's Kappa coefficient - through comparison of populated design case database of the two users , and 3) questionnaire.

In order to assess user's improved cognition in response to the identified limitation (collect partial case information), extracted key issues from the researcher's experience during population were analysed which provided clarification of evidence for assessment. The database schema required users to find case information following a given list. It enhanced user's cognition of design cases, in accordance with learning through fact-based information, as it prevented the inaccurate cognition of cases from partial case information or assumption. Regarding improvement of cognition of design cases, scale element (element number 6 in database schema, Table 4.1) was the important factor. Exact scale of cases aids correct understand about the actual form of cases and the design development environment (case image and group 2 in Database schema). According to the researcher's experience (experimentation, discussion, and observation), the actual size was sometimes different compared to the assumptions made when reviewing pictures and videos. It also found that some cases were scale-models.

In particular, tracking the number of corrections provided clarification on how well DOS supported users in learning correct information. The first database built was reviewed twice by hand through the annotation of hardcopy by the researcher. It serves as an index to reflect how well users obtained firm case information based on correct information with decreased incorrect information from assumption. In addition, the six cases were placed on each page (total 84 data elements – 6 cases*14data each). Figure 6.11 illustrates the number of corrections on the first populated database. Overall, the first review corrections are significantly higher than the second review corrections. 5.0 % (379 of 7,560 data elements) and 0.6 % (47) were edited on first and second corrections, and it means eight times the amount of elements were amended on the first review compared to the second correction. On the first review, the most corrections were carried out at the initial stage (page 1 to 25) – some pages reached at most 17.8% (15 of 84 data) in page 12, 18 and 19. After this stage, the figures are consistently decreasing. This pattern from the first review is mirrored in the second review but with a noticeably dramatic decrease - only 0.6 % (47 of 7,560) was amended. There were no corrections on half of the hardcopy (second review), and in case of modification, one or two elements in general, and up to 5 elements (page 8) are modified per page. In summary, the intensive number of corrections at the initial stage and their steady decrease provides clarification that DOS improves user's cognition of design cases based on learning according to a given list. The second review shows very small number of elements were amended compared to the first review, however, it was important to learn by confirming the changed data from the first review. Reviewing of populated database is strongly recommended at least two times.

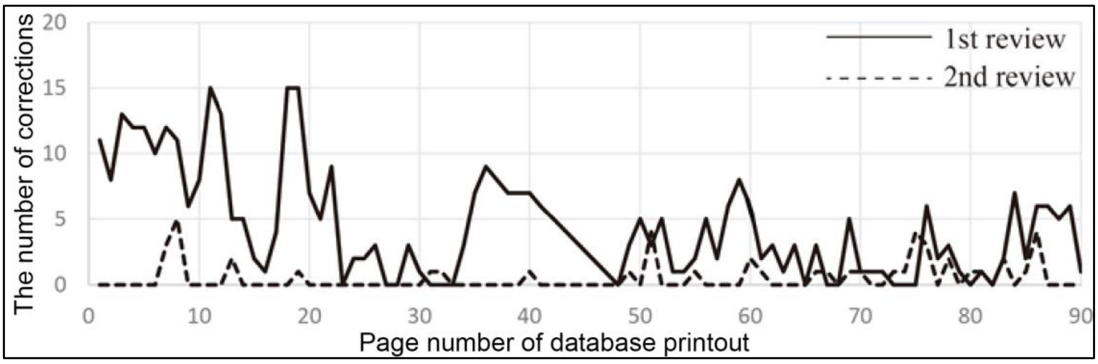


Figure 6.11 Tracking the number of corrections to DOS data

In order to assess the reliability of the database (Section 4.2.2), 13 design cases (total 156 elements) from two users were analysed through Cohen's kappa coefficient (Tang et al., 2015). As a result, the reliability of the database schema achieved 0.75 which is second highest level (Figure 6.12.c). Table 6.4 shows the correct and incorrect status of the two users, and Figure 6.12 illustrates the calculation process, result, and measurement.

(a) Cohen's kappa coefficient formula

$$K = \frac{p_O - p_e}{1 - p_e}$$

$K =$ Cohen's kappa coefficient formula. Sources from Tang et al., (2015)

$p_O =$ relative observed agreement between users

$p_e =$ the hypothetical probability of chance agreement

(b) Extracted data from table 6.4 in order to apply into kappa coefficient formula

		A		Total
		Correct	Incorrect	
B	Correct	133 (Total O)	1 (Total B)	134
	Incorrect	8 (Total A)	17 (Total X)	25
Total		141	18	159

(c) Application of (b) into kappa coefficient formula

$$K = \frac{p_O - p_e}{1 - p_e} = \frac{0.94 - 0.76}{1 - 0.76} = \frac{0.18}{0.24} = 0.75$$

$$p_O = \frac{133 + 17}{159} = \frac{150}{159} = 0.94$$

$$p_e = \left(\frac{141}{159} \times \frac{134}{159}\right) + \left(\frac{18}{159} \times \frac{25}{159}\right) = 0.74 + 0.02 = 0.76$$

(d) Agreement measures for categorical data. Sources from Landis and Koch (1997)

Kappa Statistic	Strength of Agreement
<0.00	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.0	Almost perfect

Figure 6.12. Application of Cohen's kappa coefficient. (a) Cohen's kappa coefficient formula, (b) extracted data (c) application of collected data into kappa coefficient formula, and (d) measurement criteria.

Table 6.4. Correct and incorrect status of two users

		The elements of DOS (table 4.1)															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Order of cases	1	Not applicable		O	O	O	O	O	O	O	F	O	F	O	F	
	2			O	O	O	A	a	O	O	O	O	O	O	O	
	3			O	O	O	O	O	O	O	O	O	O	O	O	
	4			O	O	O	A	O	A	A	O	O	O	O	F	
	5			O	O	O	O	O	O	O	O	O	O	O	F	
	6			O	O	O	O	O	O	O	F	F	O	O	O	
	7			O	O	O	O	O	O	B	F	O	O	O	F	
	8			O	O	O	O	O	A	O	O	O	O	O	O	
	9			O	O	O	O	O	O	O	O	O	O	O	O	
	10			O	O	O	O	O	A	0	0	0	0	F	F	
	11			O	O	O	A	O	O	A	O	O	O	O	O	
	12			O	O	O	O	O	O	O	O	F	F	F	O	
	13			O	O	O	O	O	O	O	F	O	O	F	F	
Total	O			13	13	13	10	13	10	10	9	11	11	10	7	130
	A			.	.	.	3	.	3	2	.	.	.	.	.	8
	B			.	.	.	.	.	.	1	.	.	.	.	.	1
	X			.	.	.	.	.	.	.	4	2	2	3	6	17
	Total															156

O: both are correct.
A: user a (author) is correct, and b (experienced designer) is incorrect.
B: user b is correct, and a is incorrect
X: both are incorrect/ different opinion

The storage of the populated database was the one of the desired goals in order to establish a tool for accumulation of populated databases. The researcher's experience during the population of biologically inspired design database version 2.1 (Section 4.2.2) provides a working example of an easy and reliable population process of DOS. Database schema was implemented through Microsoft's Access (commercial software), and users can easily populate data using templates through fixed input (typing, clicks for selection pre-set option, or insert image). The population of 7,560 data elements and its amendment were stably implemented without any errors. Regarding utilisation of populated data, Microsoft's Access allows them to be exported as raw data into other software. The second stage, Perceptual Mapping Generation Software, used biologically inspired design database version 2.1 as raw data. These aforementioned experiences showed that DOS provides an effective foundation for design case review with the benefits of easy population and stable accumulation.

Observation and discussion with participants during experiment 1 and 2 illustrated that DOS provided correct design case sources through a process involving amending. When reviewing the participant's hard copy the overall common reviewing process was detected – they reviewed images to find specific cases according to themes they are interested in or that are related to their current works, and then capture and populate case data. When reviewing detailed case data, an interesting situation was observed – participants specifically focused on misinformation or unknown information, and spoke with colleagues. It seems to be the specific process employed to learn correct information, and correct misinformation of design cases for accurate cognition. Discussion with some of them was conducted to ask how and where they obtained misinformation, and perform assessment of DOS. They obtained quite a lot of detailed information through assumptions from reviewing case images, and believed them to be facts over time. In response to their assessment of DOS, reviewing of the populated database highly supports the correction of misinformation and learning of unknown information along with understanding design cases with improved cognition. The questionnaire was also conducted to ask users' perception of effectiveness, difficulty of use, and likelihood of future use alongside Perceptual Mapping Generation Software, because participants used them in parallel, and data analysis will be provided in the next section.

In summary, the aforementioned analysis provides clarification of the achievement of DOS in response to limitations in the use of design case reviews: i.e. that is a risky process based on partial data and there is a lack of storage and management tools for accumulation of design case data. The database schema provides the compulsory lists to correctly understand design cases, and user's cognition improved through population, and reviewing. Database schema implementing commercial software enables easy population and storage of large sets of data.

6.3.2 Perceptual Mapping Generation Software

The Perceptual Mapping Generation Software (PMGS), the second stage of KEDIM, was developed in order to improve the perceptual mapping outcomes and generation process with respect of improving user's abilities for drawing analogies from reviews of design cases based on research by Goldschmidt and Smolkov (2006). The aims of PMGS were generation of perceptual mapping outcomes displaying an increased amount of information (design cases and their detailed information) and decreased generation time, when compared with carrying out the same task using Adobe's Illustrator. For assessment, experiments by the researcher (creation of three concepts of perceptual mapping generation according to the used software) and questionnaire by participants were carried out.

Table 6.5 demonstrates that PMGS used significantly reduced time for placing one case (0.5 seconds) compared to usage of Adobe's illustrator (240 and 1,800 seconds for 30 and 150 cases), in experiments conducted by the researcher. Further, this reduced generation time involves a displaying process of coding systems which shows additional case information. These achievements of PMGS lay the foundation that enhances novice designers' abilities to draw analogies for inspiration (Chuang and Chen, 2008), through providing improved data exploration and defining abilities (Ho, 2001; Dinar et al., 2015).

Table 6.5 Summary of the results of the three groups of perceptual map generation software

	Conventional outcome	**Empirical research**	**PMGS**
Used software	Adobe's illustrator		PMGS
The number of cases	30	150	540
Used time per case	240s	1,800s	0.5s
Used time for first generation (s=seconds)	2 hours (=7,200s)	60hours (=216,000s)	5 minute (=300s)
Used time for revision (change Y axis)	30 minutes (=1,800s)	3 hours (=18,000s)	1 minute (=60s)
Time efficiency unit	1	7.5	0.002
The number of pieces of data per case	3	6	Maximum 8
The number of pieces of data	90 (30*3)	900 (150*6)	3,240 (540*6) Maximum4,320 (540*8)
The considered role of user	Chart generation		Case analysis

The generation process from two outcomes (conventional way and empirical research) using Adobe's Illustrator highlighted that production time was significantly increased as the number of cases increased and coding systems were added. It is noteworthy that the empirical research outcome involves five times the cases, however results in thirty times the generation time spent. After conducting the experiment process analysis revealed the major cause of this is the inefficiency of used tools: the researcher placed each case by comparison with relevant cases. It was also apparent that the researcher spent quite a long time for generation of perceptual mapping outcomes.

Compared to this situation, analysis results of PMGS provide evidence that it significantly reduced time for generation. PMGS only took 5 minutes to generate perceptual mapping outcomes involving 3,240 (540 cases * 6 pieces of data for each case) as shown in Figure 3.6. This outcome can increase the amount of information displayed to 4,320 (540 cases * 8 pieces of data for each case) with increased data through coding from 3 to 5, and also took five minutes. In particular, PMGS allows coding (selection of information, and colour) to be designed and used automatically, compared to the other two outcomes which need to be edited by hand, this supports users with improved drawing analogies based on the changed role of the user (through decreased generation time). Reliability of the database populated was assessed to 0.75 according to Cohen's kappa coefficient in section 6.3.1, with Coding to visualise this data. Therefore, the reliability of coding is also assessed as being substantial (0.75).

In summary, PMGS can generate perceptual mapping outcomes involving a high number of cases (and their detailed information) through coding within an exceedingly decreased generation time compared to the other two experiments. PMGS took 0.5 seconds to place one case according to the axis definition, and mark coding including five data items based on the populated database. On the other hand, conventional and empirical research used 240 and 1,800 seconds for one case. This made it evident that PMGS achieved a high degree of working time efficiency compared to the other two methods. According to time efficiency unit data, the developed method achieved a much shorter making time, as it (0.002) recorded 500% (1/0.002) and 3,750% (7.5/0.002) increased time efficiency compared to the other two methods. Additionally, used time per case of general cases (4 minutes per case) is referred to as a single unit (1), and smaller and bigger numbers mean higher and lower time efficiency. Also, this number scope needs to be bigger than 0. The perceptual map generation software uses a similar amount of time (5 minutes) regardless of the number of cases for generation of outcomes, and the revision process only requires around 1 minute. Consequently, this software seems to be an effective solution to explore quantitative research, idea variations and qualitative image sources and define implicit patters at the design concept ideation stage.

The notes taken by the researcher provide detailed assessment of user's perception during the usage of PMGS. It was shown that PMGS enables the display of a significantly increased number of design cases through increased stimulation (Goldschmidt and Smolkov, 2006). It must also be noted that this could also be considered as causing confusion. The coding system marks a maximum of 5 data elements through colour circles on each image according to definition by the user (in Section 4.3.2). It was designed to deliver extra information and the overall situation of cases in order to decrease the possibility for confusion. Based on the review of outcomes with coding (Figure 3.6 to Figure 3.10, and Figure 4.8 and Figure 4.9), coding intuitively delivered detailed case information in a simple, visual way. At the initial stage of reviewing outcomes involving 150 and 540 cases, coding clarified the overall situation such as common, or specific issues. For instance, Figure 4.9 (a) and (b) have the same case and coding definition, and X axis, with only the Y axis being different as Scale and complexity of solution. Firstly, (a) and (b) indicates that 1) the number of bio-inspired designs has been dramatically increasing, and 2) the percentage of designers using the latest design development tools and methods has been increasing since the year 2000. In (a), the majority of cases with red coding are on a scale under 100 cubic centimetres (Y axis). And (b) shows that the latest design development environments are specifically used for highly complex solutions (4 and 5). These findings indicate that the utilisation of the latest technologies is being applied for small sized products, providing high complexity of form compared to design cases using traditional technologies. These findings might bring forth relevant questions or specific exploration to focus on narrow parts of outcomes – then users can observe design case images with coding for exploration.

According to the questionnaire results, ‘effectiveness’ and ‘likelihood of future use’ of PMGS with DOS were assessed as achieving a highly positive evaluation, and ‘difficulty of use’ was considered as ‘moderate difficulty’. 61 participants (experiment 1 and 2) reviewed hardcopy outcomes from DOS and PMGS, and then directly used PMGS. Once completing these stages, questionnaires were used to ask users’ perception of effectiveness, difficulty of use, and likelihood of future use. Figure 6.13 illustrates the results of the questionnaire.

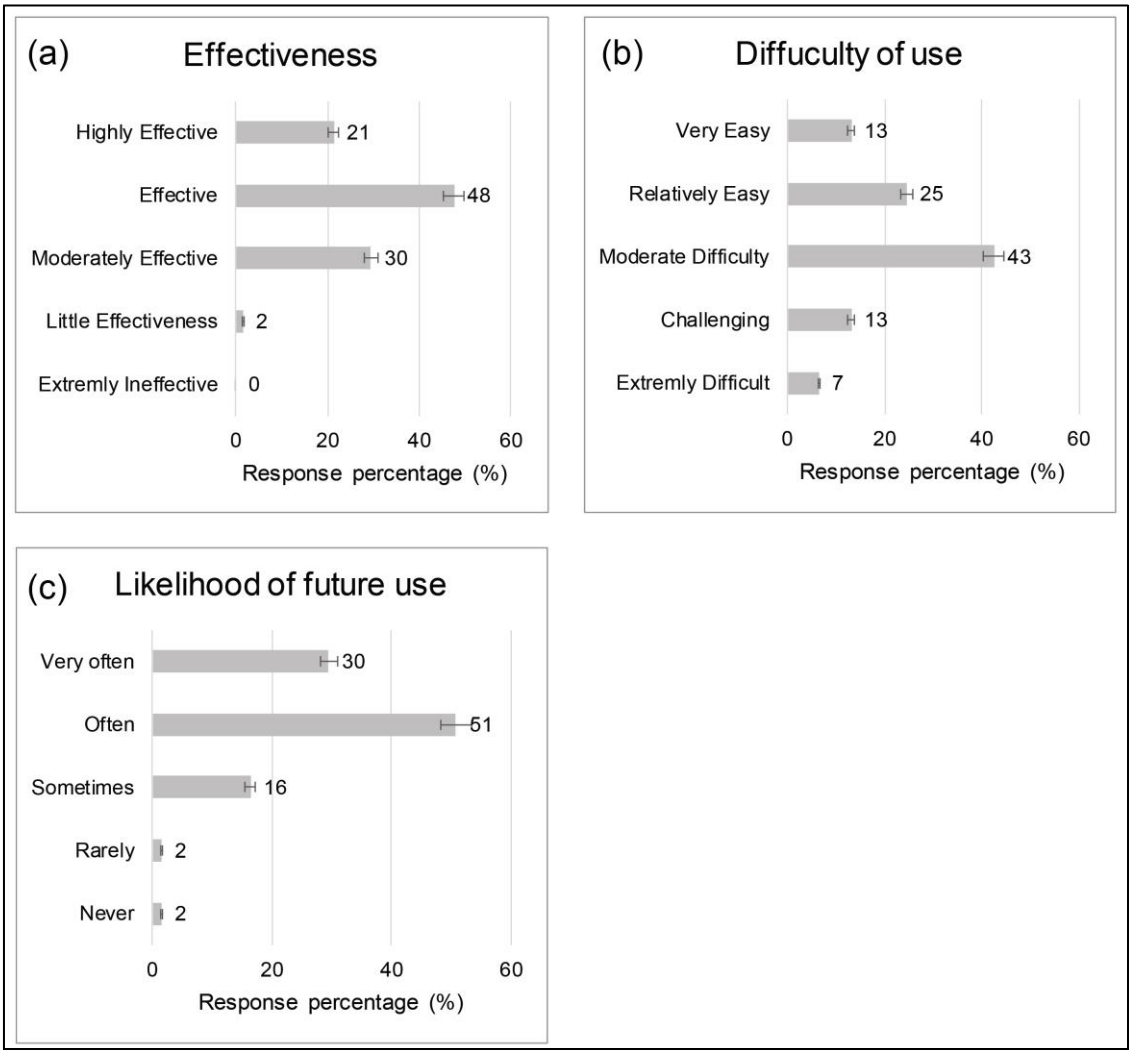


Figure 6.13 Questionnaire results for design case and PMGS by participants. Results shows ± five percent standard error

In detail, effectiveness and likelihood of future use were assessed as quite positive with 69 and 80 percent (sum of response to two positive answer options). The majority of respondents want to use these tools - very often (51%) and often (30%) in response to the likelihood of future use question. 'Moderate Difficulty' (43%) was selected the most in assessment of 'Difficulty of use'. The percentage of negative answers (sum of response to two negative answer options) was significantly high at 20 percent, compared to effectiveness (2%) and difficulty of use (4%). These results were reviewed in more detail with descriptions of experiments. Participants asked many questions to obtain understanding of the hardcopy and the concept of the tools. It was an unexpected situation that was caused by the gap in the degree of knowledge of tools and their outcomes. The researcher, as the person who developed them, can naturally obtain a high degree of understanding, whereas, it seems that users need more detailed information for usage and outcomes, and additional time to understand and learn. In particular, participants faced a situation that required understanding large numbers of design cases (populated database) and to explore them through PMGS within limited time. These results need to be discussed in order to establish the learning guideline for users. Regarding development status of tools and analysis results, the revision of instructions was considered to provide clearer guidelines and stages, and allowing more time in order to enhance the learning process through alleviation of these difficulties faced by novice designers, and revision of tools was not considered.

In summary, the Perceptual Mapping Generation Software (PMGS) was assessed through the ‘comparison of three experiments’ and ‘discussion and observation from group experiments’, with respect to enhancement of users’ abilities to draw analogies from case review through conveyance of increased information (number of the cases and their detailed information). The aforementioned data confirmed the validity of PMGS through comparison with two conventional methods - PMGS has the capacity to display a significantly higher number of cases, and mark their detailed information through visualised coding. The coding specifically illustrates the overall situation of cases, and it allows users to understand large amounts of information. The generation time was also drastically reduced. In conclusion, PMGS provides novel ways to convey large amounts of design case information with improved display methods through perceptual mapping. These outcomes were generated within a significantly reduced time, and it encourages users to focus on analysis through generation of diverse outcomes in response to emerged questions. User perception of ‘effectiveness’ and ‘likelihood of future use’ was highly positive. The guidelines provided for the users need to be revised in further works for ease of understanding as users’ perception regarding ‘difficulty of use’ was recorded as ‘moderately difficult’. Enhanced guidelines should rectify this issue. Overall, these results demonstrate that PMGS enhances user’s abilities of drawing analogies from design cases by providing increased appropriate stimulation and information.

6.3.3 Systematic Brainstorming Ideation Method

Systematic Brainstorming (SBI) was developed to provide users with a systematic idea generation development process through a set of specific ideation themes. The three data types collected were assessed for comparative analysis between two groups, using SBI or blank paper. Firstly, differences of ideation development were analysed through the reviewing of sketching outcomes with three perspectives (observation of ideation process, the number of ideas generated, and classification of ideation outcomes). Secondly, user perception of effectiveness, ease of use, and likelihood of future use were assessed through the statistical analysis of the questionnaire. Thirdly, description of observation and discussion during experiments was used for detailed assessments.

As preparation, completed sketching outcomes were restructured (from Figure 6.14 to Figure 6.16) in order to analyse properties of ideas and their correlation along with a set of specific ideation stages. Ideation performance with brainstorming between SBI and blanks paper users was analysed using the restructured sketching outcomes.

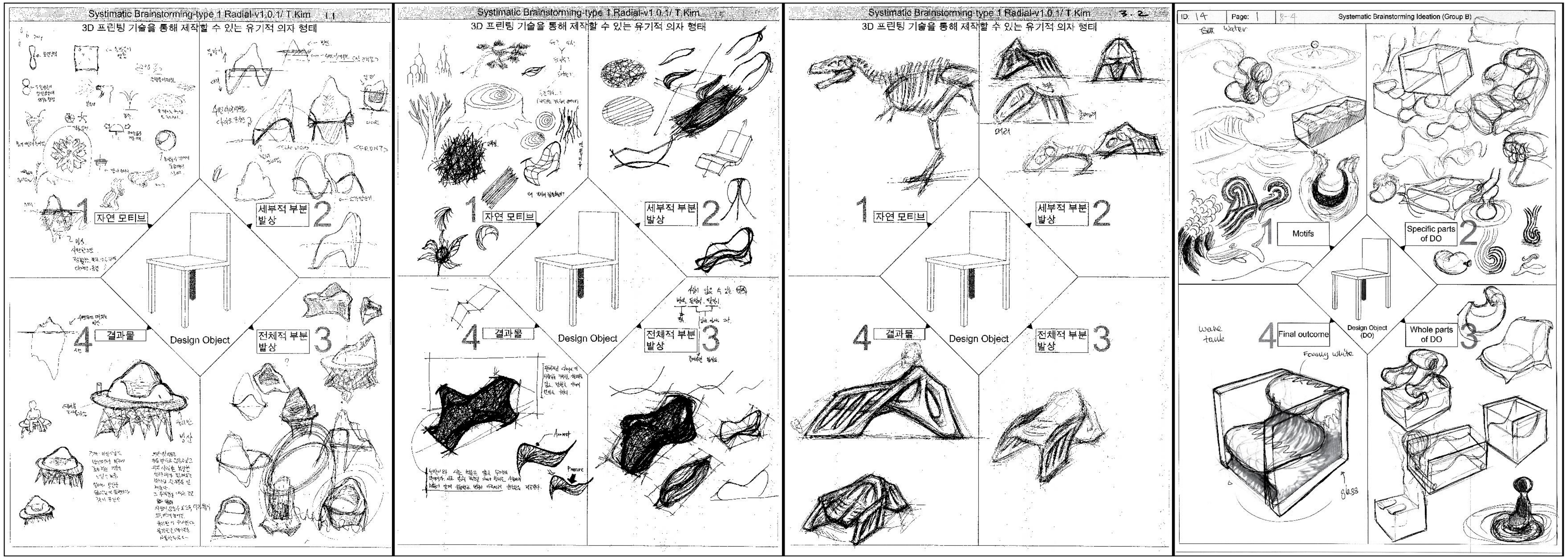


Figure 6.14 Examples of completed SBI templates

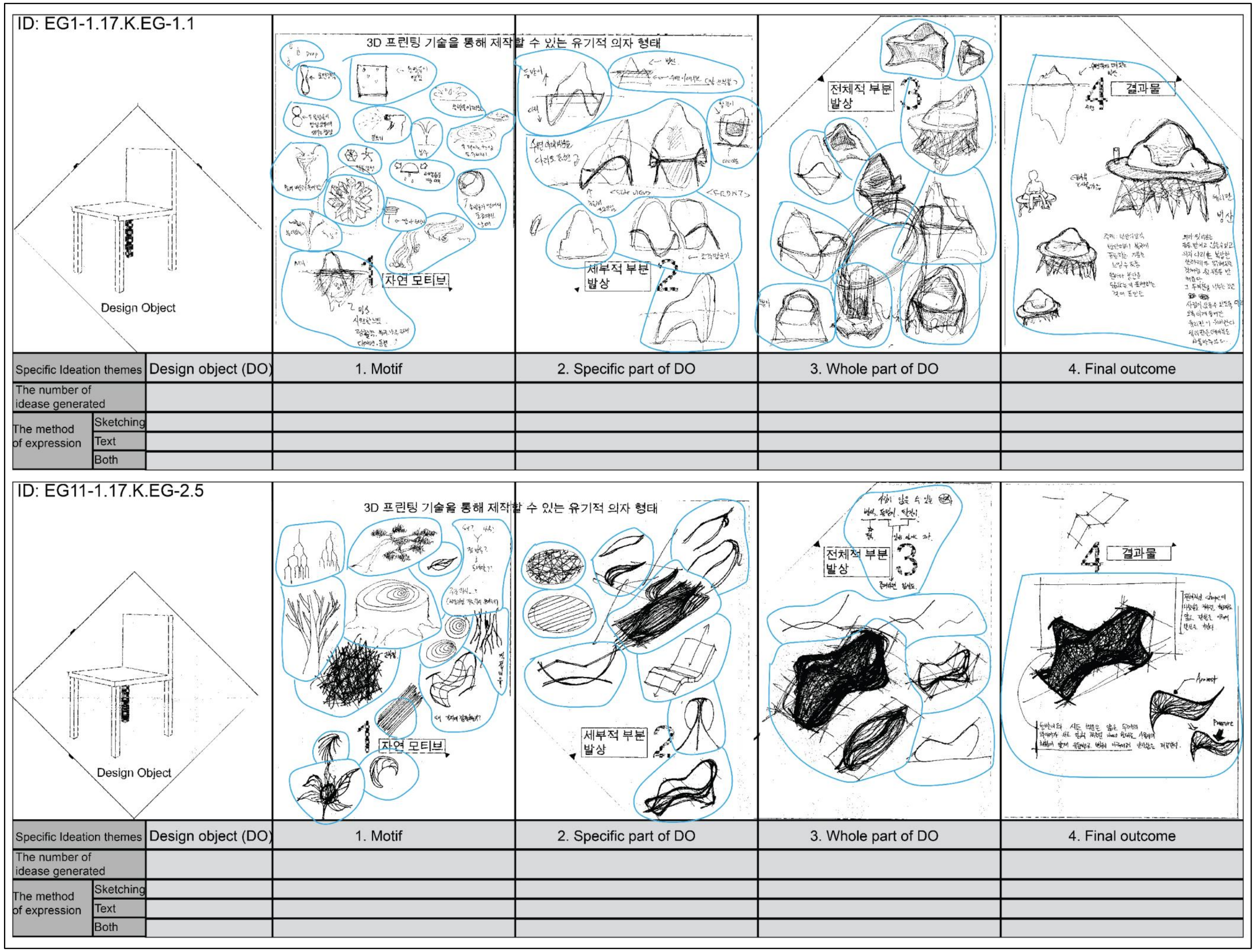


Figure 6.15 Examples of restructured sketching outcomes

The number of ideas generated were counted in order to measure the effectiveness of the ideation process (Shah, 2003), and comparison of the results from two groups shows how well SBI enhances an effective idea generation process. In this analysis, brief guidelines were established to refer to the concept of idea – three types of ideas according to the method of expression (sketching, text, or both), and ‘groups of similar ideas’ and an ‘idea with deletion mark’ were counted as one. According to this guideline, each of the ideas were counted (blue circles in Figure 6.15). In addition, it is important to inform the identified guideline issue before explaining analysis results: the changed analysis result according to the guideline. In the preliminary analysis process, ‘groups of similar ideas’, such as Figure 6.19. b-1, was identified as the problematic variation that can potentially cause the inaccurate counting of total numbers of ideas generated (quantity by Shah (2003)). A specific instruction or guideline was not given in response to this situation in (Shah, 2003). Accordingly, the preliminary research reporting the analysis results including this variation (Kim et al., 2019) illustrates the different results to those in this thesis (Table 6.6 and Figure 6.16) depending on the guideline. Overall, both analysis results commonly show the improved number of ideas generated by SBI users compared to control groups. The average number of generated ideas are changed from the preliminary results to the thesis: the UK CG (a control group): no changes/ the UK EG (an experimental group) from 25 to 23.5/ Korea CGs: 9.2 to 7.3/ and Korea EGs from 12.2 to 13.). The analysis results were randomly increased or decreased. This aforementioned context makes it apparent that the evaluation method (quantity by Shah (2003)) for SBI provides more accurate analysis results which eliminate variation (groups of similar ideas).

Table 6.6 and Figure 6.16 show the analysis result of the number of ideas generated by comparison of control and experimental groups. They validate that SBI users in the UK and South Korea generated 22 and 85 % more ideas compared to those following an unstructured method (blank paper). The total result is 6 %, and this figure is consistently lower compared to the imported data from the UK and South Korea. Simpson’s Paradox refers to a phenomenon which occurs when the degree of percentage within each group does not necessarily correlate to the total percentage. It occurs from a third variable (Z) which had not been considered, against the considered pair of variables (X, Y) (Pearl, 2016), and it was confirmed by a Korean mathematician (expert). In this sense, the variables considered (X, Y) is the number of ideas generated and participants, and the third variable (Z) is the different number of participants in the four groups. The numbers of the control and experimental group in the UK and South Korea are 14, 16, 26 and 77. According to the average number of ideas generated, UK and Korean control groups are recorded as 19.2 and 7.3, and their sum is 14.3 (24 participants generated 342 ideas). UK and Korean experimental groups are 23.5 and 13.0, and their total is 15.2 (77 participants generated 1,167 ideas). These results demonstrated a significant increase, their total difference was 6 percent, and the reason for this is the difference between the control and experimental groups according to countries. UK control and experimental groups generated 160 and 80 percent more ideas compared to Korean participants. In each country, experimental groups generated more ideas compared to control groups, however, the result of the UK control group is much higher than the Korean experimental groups at 19.2 and 15.2. The lowest and highest results are 7.3 (Korean control groups) and 23.5 (the UK experimental groups).

Table 6.6 The average number of generated ideas

	Control group (CG)	Experimental group (EG)	Result (increased % of EG)
Brainstorming format	**Unstructured - Blank paper**	**SBI**	
United Kingdom	Total: 19.2 (269/14)*	Total: 23.5 (376/16)*	22%
South Korea	Total: 7.3 (73/10)*	Total: 13.0 (791/61)*	85%
Total	Total: 14.3 (342/24)*	Total: 15.2 (1,167/77)*	6%
*(a/ b): ‘a’ and ‘b’ means the number of ideas generated, and participants			

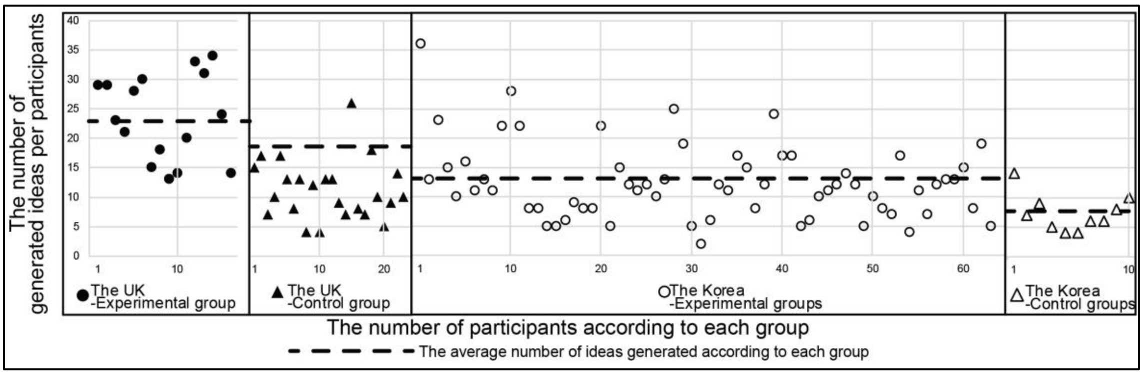


Figure 6.16 The number of idea elements generated by all participants

Increased stimulation through analogical reasoning based on the design brief is closely related to the increase in creative ideation performance (Goucher-Lambert and Cagan, 2017). In this sense, the verification of how well ideas consider the requirements from the design brief clarifies the improved creative ideation abilities through the Systematic Brainstorming Ideation method. Overall, almost all of the participants considered the given design motifs and object, yet use of additive manufacturing technology differed. Table 6.7 illustrates that the experimental groups generated more than twice the number of ideas that considered additive manufacturing technology (17.9%) compared to the control groups (8.6%). This gap is more remarkable compared to the number of ideas generated which is 6% higher (Table 6.6). Based on this evaluation result, Systematic Brainstorming Ideation supports novice designers' creative ideation performance through the increased understanding of multiple information categories and its development.

Table 6.7 The number of ideas relevant to additive manufacturing and its percentage

	Number of participants	Number of ideas generated	Number of ideas relevant to additive manufacturing technology	
			Number of ideas	Percentage
Experimental groups	78	1145	206	17.9%
Control groups	26	361	31	8.6%

The potential causes for these differences between countries were analysed using the observation and discussion carried out during the experiments. 1) Lecture style during experiments, and 2) participants' mind-set for class and ideation. In the UK, the lecturer did not intervene or give advice during the experiments, and participants generated ideas to express their thoughts for expansion or exploration. On the other hand, in Korea, a lecturer intervened and gave feedback during the workshops, and although participants generated ideas in the same way as UK participants, they also communicated with their lecturer. This situation interrupted participants' ideation performance and made them feel under pressure. The lecturer affected outcomes within the ideation process of individual participants (as can be seen in Figure 6.17) by drawing on their worksheet and making direct suggestions for changes. A negative impact on the participant's ideation performance was noted by the reviewer. These findings have been considered to establish guidelines for lectures in further works. It should be noted that these experiments were conducted in two different universities, one in the UK and one in Korea, therefore these results cannot be seen as being fully comprehensive.

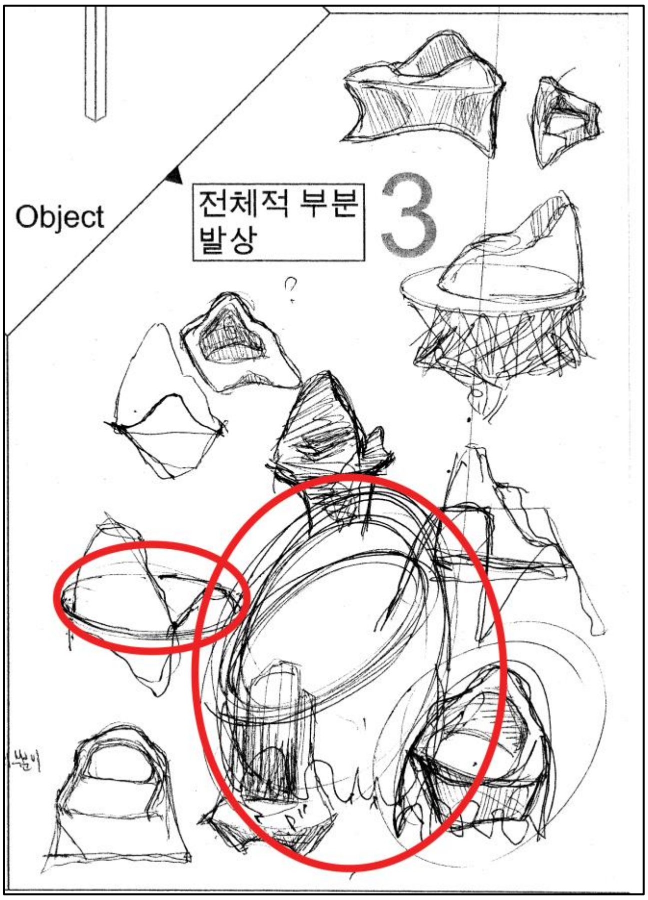


Figure 6.17 Example of intervened mark by lecture – Whole part of design object of SBI. Participant ID: EG 1, Experiment group 1, location: Korea

Performance of idea generation was assessed through the analysis of the distribution of ideas according to two perspectives, a set of specific ideation themes, and methods of expression. The first perspective clarifies how well participants dealt with and discussed the specific ideation themes along with developing a solution in response to the design brief. The second perspective reflects how well participants described faced difficulties or gave detailed description of their idea concept through the appropriate methods of expression. These actions are required for novice designers to be compared to experts in perspective of effective ideation performance, and the guideline of method of expression was provided at the initial stage of the experiment (Section 5.6 for detailed information). The comparison between experimental and control groups demonstrates the achievements of SBI according to its desired goals.

Figure 6.18 (a) shows the distribution of ideas according to a set of specific ideation themes – motif, specific part of design object, whole part of design object, final outcome, and design object. The distribution between experimental and control groups is significantly different. Control groups mainly generated ideas for the whole part of design object (61.4%), and other specific themes were less developed – motifs

(26.3%), final outcomes (6.4%), and specific parts of design object (5.8%), in the UK and Korea. The UK and Korea results also show a similar tendency (Figure 6.18 (a.1) and (a.2)). On the other hand, the distribution of ideas from experimental groups shows that the largest percentage is on the motif stage, the first stage of a set of specific ideation stages, and then steadily decreases over sequential ideation stages. In summary, control groups are prone to using limited ideation themes with lack of consideration other themes, however, experimental groups develop solution through the phased ideation themes.

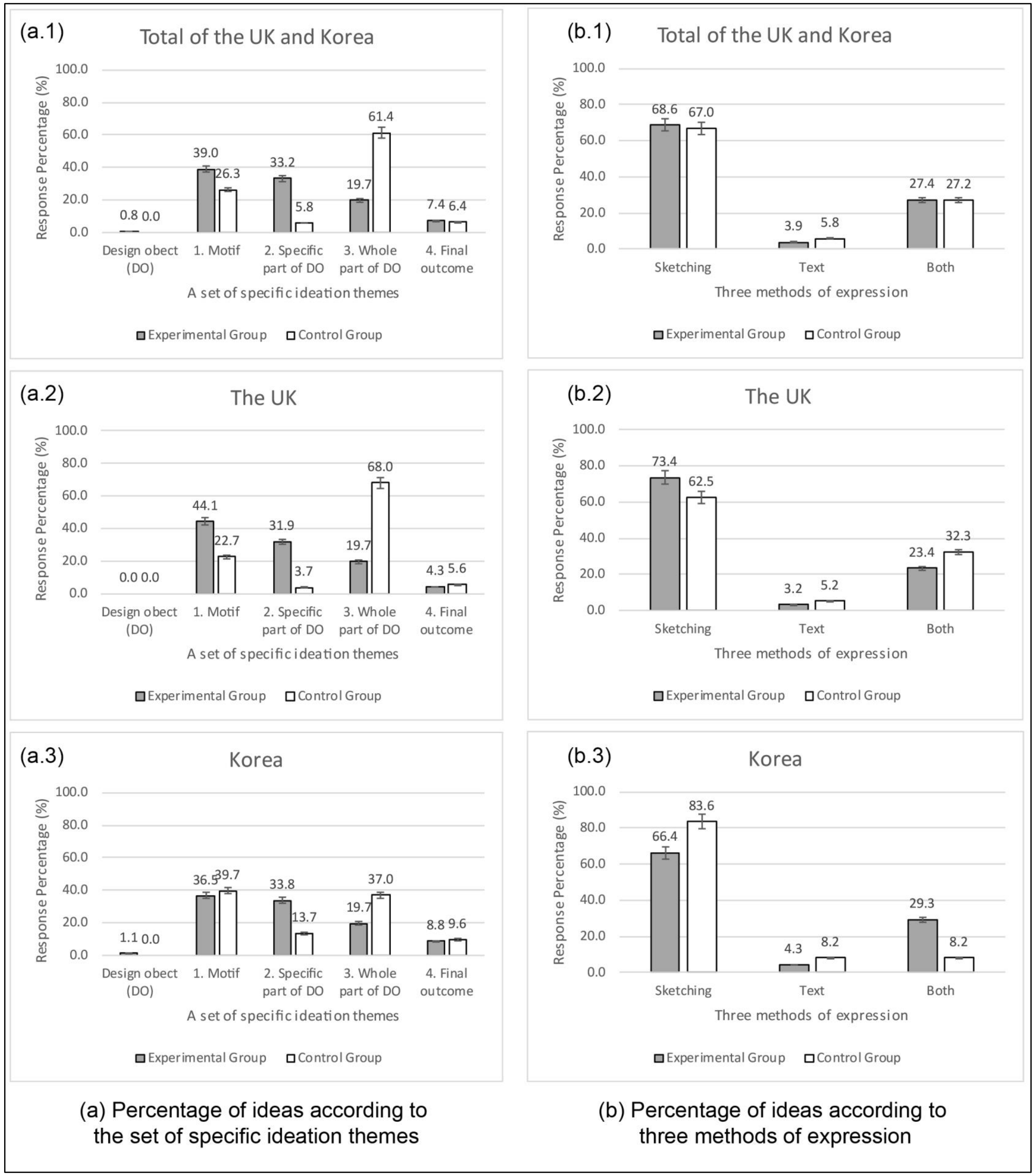


Figure 6.18 Distribution of ideas generated according to a set of specific ideation themes and method of expression. Results show ± five percent standard error

Figure 6.18 (b) provides the distribution of ideas generated with respect to the methods of expression according to control and experimental groups and countries. Overall, it shows quite similar tendency in the three categories (Figure 6.18. b.1, b.2 and b.3)). In particular, the guidelines for text and both (sketching + text) were provided for recording faced difficulties and description of concepts, and this issue was reviewed. The percentage of ‘Both (sketching + text)’ is almost same between the experimental (27.4%) and control group (27.2%), and sketching (68% versus 67%) and text (3.9% versus 5.8%) also show similar results in the UK and Korea. Some gaps exist in the UK and Korean results, however patterns or specific differences are not identified in statistical data. In the analysis of ‘observation of ideation process within sketching outcomes’, the differences in the degree of text context were identified between the two groups. In the experimental group, the text context sometimes involves description of faced difficulties or detailed explanation of a concept in the final outcome section (Figure 6.19. a). On the other hand, the control group mainly used text for simple words to refer to motifs (Figure 6.19. b.1), or functions (Figure 6.19. b.2).

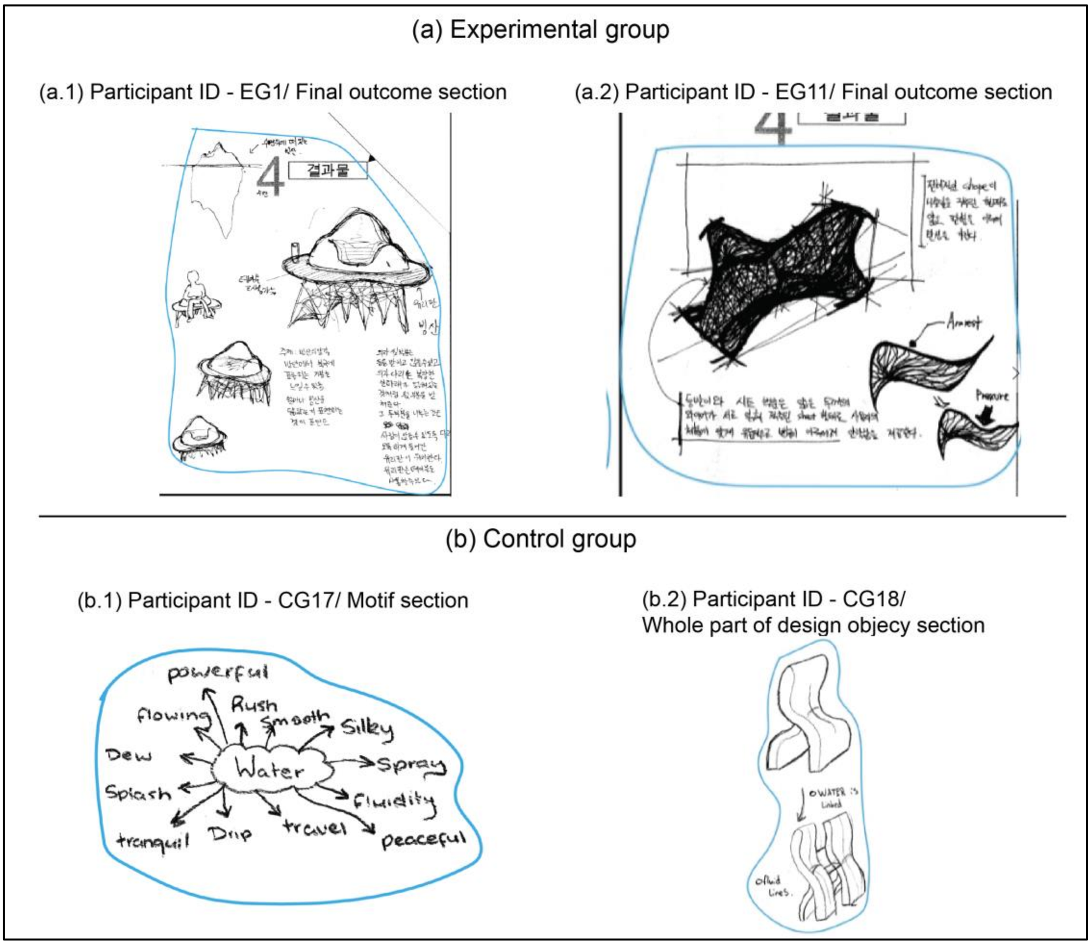


Figure 6.19 Examples of text context in experimental and control groups

The aforementioned validations were observed properties of ideas generated. Their correlation alongside the solution development process was analysed through reverse tracing from final outcomes to the directly related ideas based on restructured sketching outcomes (Figure 6.20). Empirical studies report the properties of experienced designers' solution concept development processes (Section 2.3.2): beginning with comprehensive searching for relevant information and cues, and then developing in depth ideas (Ho, 2001; Shah, 2003; Self, 2017). If difficulties are encountered, the expert switches to a depth first identification of the required information (Ball et al., 1997; Ho, 2001). Accordingly, tracing of ideations aimed to identify the correlation of three ideas: 1) identify the idea development process which is directly related to the final outcome, 2) idea's merging or specification as development, and 3) shifting of ideation themes.

Figure 6.20 shows the examples that mark ideas which directly related to final outcomes and their correlations, with two types of examples involving the highest and average number of ideas in the experimental and control groups. These examples describe the different characters of the two groups' outcomes.

Overall, the control group, using blank paper, generated few ideas that relate to the final outcome. Ideas tend to focus on breadth-first exploration, and this causes a lack of consideration with other ideas. In the outcome involving the largest number of ideas (21 ideas, see Figure 6.20 - b.1), three ideas are closely related to the final outcomes, and their development seems to be a simple linear process. Figure 6.20 - b.2 shows similar situation but with more critical results. It involves 14 ideas (with an average of 14.2), however the final outcome emerged without consideration of ideas in the previous stage. These properties have a relationship with the ideation processes reflected by novice designers reported in the literature, i.e. concurrent and unsystematic processes (Kavakli and Gero, 2002), avoidance of ideation difficulty (Dinar et al., 2015), with ideas emerging spontaneously without clear connections or a logical development process. The results from the control group experiments also showed a complex mix of ideas, disturbed concentration and confusion, and so decreased the attainability of a systematic ideation process and correlation among ideas.

On the other hand, the experimental groups using SBI achieved a more successful ideation process compared to the control groups. The number of ideas relating to the final outcome were significantly higher with enhanced correlation compared to control groups showing a systematic process. Responses exhibited a logical ideation performance (from tacit motifs to explicit ideas), idea generation based on correlation of previous ideas, and proactive activities when faced with difficulties. The ideas were intensively produced and the relationship between the four themes was also enhanced. These preliminary results indicate that the four ideation themes of SBI provide clear and specific objectives to users resulting in a structured ideation process, akin to that of experienced designers (Kavakli and Gero, 2002).

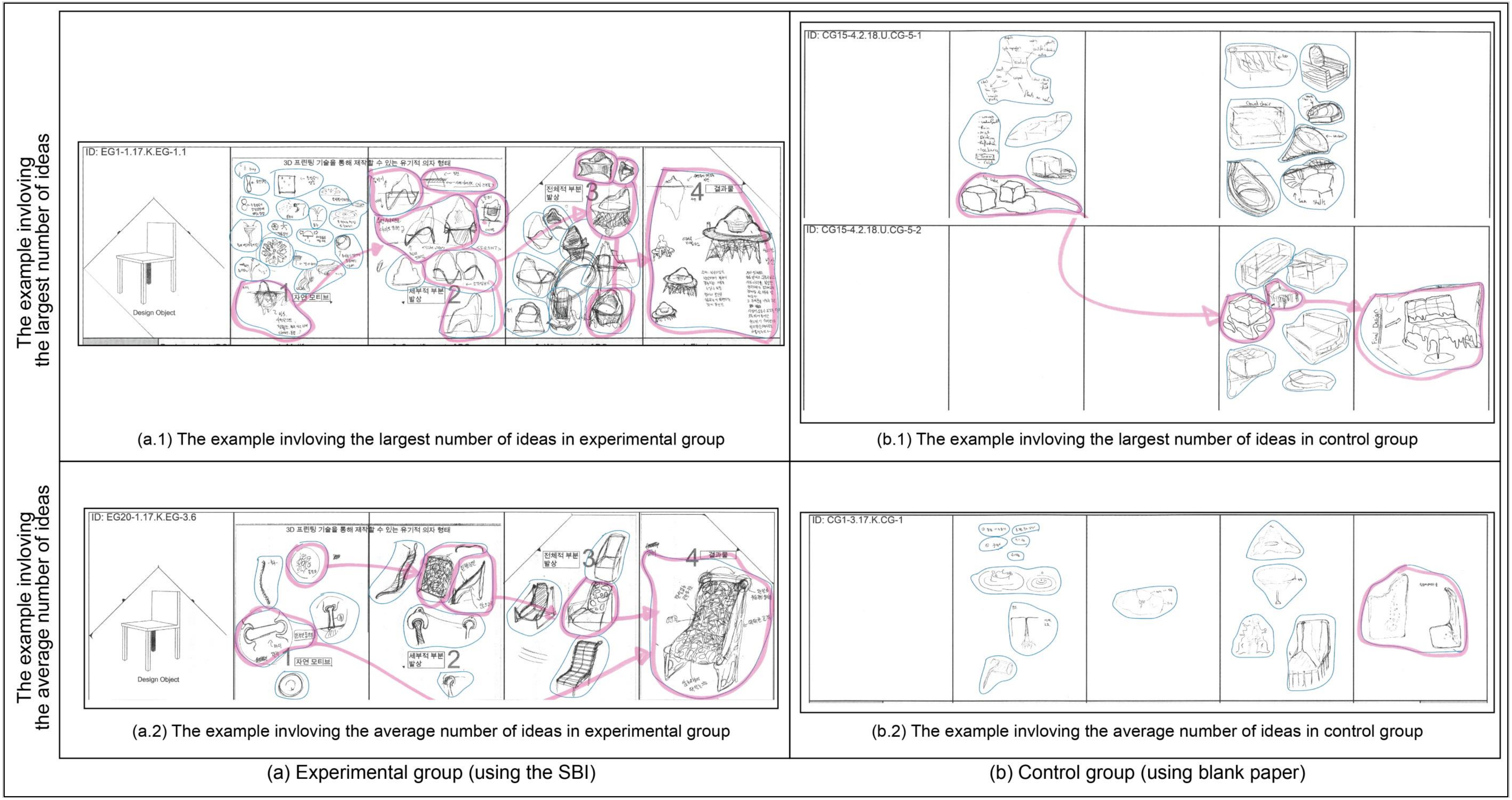


Figure 6.20 examples of ideation development process

In addition to this analysis, participant perception about effectiveness, ease of use, and likelihood of future use was assessed through a questionnaire completed by 96 of the 101 workshop participants after the ideation workshop. The results, shown in Figure 6.21, indicate that the majority of participants positively evaluated SBI, with consistently better responses compared to the use of blank paper. Responses for SBI and unstructured (blank paper) are summarised as: effectiveness (63.5% vs. 50.0%); ease of use (47.3% vs. 31.8%); likelihood of future use (64.9% vs. 63.7%). The usability findings indicate that SBI is more easy and effective, particularly considering that participants were using SBI for the first time during the experiment. It is noteworthy that SBI is reported as being easier to use than blank paper, which is expected to be a familiar method. This highlights the fact that SBI makes the ideation process easy and intuitive for novice designers as it leads them through specific ideation stages. Feedback also noted the effectiveness of SBI with participants ranking the effectiveness twice that of the control group using blank paper.

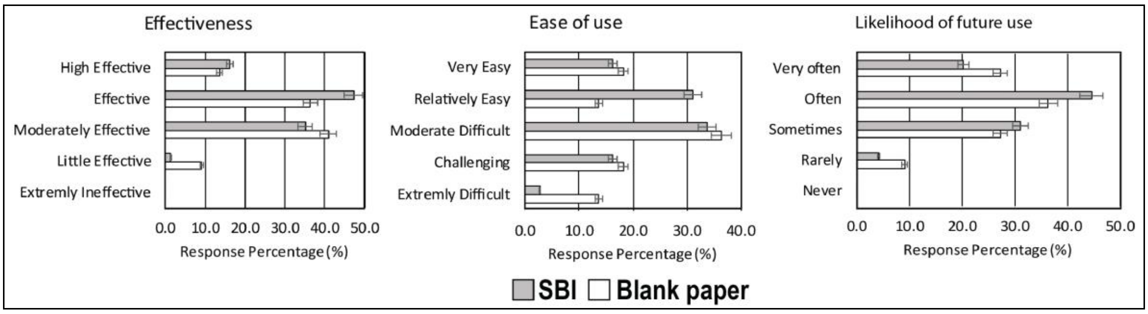


Figure 6.21 Comparative evaluation between SBI and blank paper. Results show ± five percent standard error

SBI was established to replace blank paper due to the aforementioned merits. However, consideration of mixed methods arose from the discussion with the participant conducting individual work. This participant used blank paper and SBI in turn for the first 4 weeks, and used them according to individual preference for the next 4 weeks With a brief postscript being collected from these experiences. Blank paper was preferred for exploring of relevant design brief data at initial stages with improved sequential data collection stages. These collected ideas could be well structured following a set of specific ideation themes providing SBI alongside user’s solution concept development. Although this issue was identified during the individual workshop, it need to be elucidated through additional analysis and evaluation experiments in further works. The analysis of recorded video that captured participant’s ideation scenes with coding will be additionally implemented for the purpose of comparison analysis in future work.

6.3.4 Knowledge-Enabled Design Ideation Method

The aforementioned assessments of the three tools were drawn into the evaluation of KEDIM with respect to how well users switch to the next available tools based on technical linkages. The obtained knowledge from previous tools, as medium, were closely related to the outcomes in the next sequential tool used. The technical movement from first (DOS) to second stages (PMGS) was carried out via digital file (accdb type: Microsoft Access Database). An accdb file involving populated database import to PMGS as raw data. The degree of understanding of the populated database is essential in order to effectively achieve the desired goals of PMGS – drawing analogies from design case review - because it will affect what information the user will create and explore through PMGS.

The second (PMGS) and third stage (SBI) were linked by analogies obtained from design cases. These analogies were drawn to improve ideation performance followed by a set of specific ideation themes in SBI. The consideration of 'method of use for SBI and blank paper' according to the faced situation arose from the discussion with individual work participants. Validation through sketching outcomes confirmed that SBI enhanced ideation performance compared to the blank paper in group experiments, however the establishment of a guideline is required in further work.

The aforementioned analysis of data shows that the three tools of KEDIM are well linked technically, and users focus on obtaining the appropriate context from each tool because it is the medium that are closely related to the result in the next sequential tool. In conclusion, KEDIM establishes an intensive ideation method to improve novice designers' effective performance. In addition, further evaluation experiments with fixed participant groups who use all three tools of KEDIM will be undertaken to collect consistent assessment for components and their correlation within KEDIM (see Section 7.3).

6.4 Summary

This chapter reports results from the evaluation of the three tools of KEDIM and the interfaces that link them, and offers a detailed description based on experiment data. In evaluating each tool of KEDIM, an analysis was provided that elaborated researcher and user (group and individual working) perspectives.

The results gained from the evaluation experiments provide evidence that each tool achieved its desired goals. The Perceptual Mapping Generation Software (PMGS) creates perceptual mapping outcomes in novel ways based on the populated database in the first tool. A significant decrease in making time needed to generate a perceptual map facilitates the display of large amounts of information (cases and their detailed information) in a graphical form through the perceptual mapping outcomes. The coding system used enables the visualisation of detailed case information through the use of circles on each image as tags which are discussed in Section 4.3.2 and 4.3.4. Participants positively evaluated the effectiveness and likelihood of future use of DOS and PMGS. However, difficulty of use was ranked as 'moderately difficult' indicating that further work is needed to provide a more easy method of use through guidelines and revision of interfaces. Systematic Brainstorming (SBI) enhances ideation performance. In analysing the number and distribution of ideas from the experimental data, SBI users generated more ideas – 85%, 22%, and 6% in the UK, Korea, and in total - following a set of specific ideation stages. On the other hand, blank paper users focused on 'whole part of design object (61.5%)' with a lack of consideration for other themes. The questionnaire results indicate that the majority of participants positively evaluated SBI compared to use of blank paper. This result is significant, particularly considering that participants were using SBI for the first time during the experiments.

The analysis of experimental data demonstrates the achievement of KEDIM according to the desired goals in response to the knowledge gaps. In an attempt to develop KEDIM, the experimental design and analysis completed was supplemented with findings on how the study will contribute to knowledge and limitations for future work. The implication of these findings is discussed in Chapter 1, where considered alongside the experimental design and data analysis(Chapter 1 to Chapter 1).

Chapter 7 – Conclusion

This research was inspired by the emergence of advanced manufacturing technologies, such as additive manufacturing (3D printing), that provided exciting new opportunities for product design by enabling the design and manufacture of new kinds of forms that could not previously be realised. Designers' exploitation of these opportunities depends on their ability to incorporate potential new manufacturing capabilities in their design ideation processes. A key research challenge lay in maximising the human creativity and ingenuity of designers and other stakeholders while also exploiting the power of technology-driven developments in both manufacturing and computing through the design of forms that deliver required product behaviours. This led to an initial investigation of bio-inspired design and the recognition of the requirement for methods and research to support novice designers in the use of bio-inspired design and other forms of design by analogy (Fu et al., 2014). Chapter 1 reviewed the role of ideation within design processes, and identified requirements for ideation methods for novice designers that would improve their design ideation performance in terms of the number of concepts generated and the variety across them. The main conclusion from this review was that, when compared with expert designers, design ideation is more challenging for novice designers who have limited experience on which to draw and no systematic process to follow. Existing ideation methods mainly focus on specific parts of the ideation process but not the process as a whole. Accordingly, a need for a systematic ideation process was identified, to provide a structured process from the design brief to solution concept generation, and to expand the range of sources of inspiration used.

In response to this need, Knowledge-Enabled Design Ideation Method (KEDIM) was proposed and evaluated using Design Research Methodology Type 5 (Blessing and Chakrabarti, 2009). KEDIM includes three stages of ideation: reviewing sources, drawing analogies, and generation of solution concepts. For the first stage of KEDIM, a Database of Design Cases (DOS) was developed to provide a structure to capture design case data and so give users a wider range of sources and further case information in response to the limitation of users tending to collect partial case data. Perceptual Mapping Generation Software (PMGS) for the second stage, is used to visualise data from DOS in a way that enhances users' abilities to draw analogies. The third stage, the paper template for brainstorming, was developed based on the SECI theory (Nonaka et al., 2000) to provide a structured concept generation process supported by ideation themes drawn from DOS, called Systematic Brainstorming (SBI).

7.1 Research contribution

This thesis establishes a method that enhances the design ideation performance of novice designers by providing a systematic design ideation process for them to follow. The method was assessed through empirical evaluation experiments conducted with 101 students in the UK and South Korea, by the researcher. This confirmed the overall contribution of KEDIM: that it improves novice designers' generation of creative solution concepts in response to a design brief. The research makes four contributions. Firstly, Knowledge-Enabled Design Ideation Method (KEDIM) itself provides a systematic design ideation process that includes three steps (DOS, PMGS, and SBI). KEDIM provides an overall architecture that enhances the ideation performance of novice designers by providing a systematic process for design ideation. In the development process of KEDIM, the major objective considered was the creation of an ideation method that was suitable for use by novice designers. Questionnaire results from participants rated the difficulty of use of the three tools of KEDIM as similar or more easy compared to the common methods used (e.g. case study, perceptual mapping, and brainstorming), despite them being used for the first time. This assessment also indicates that participants felt satisfaction from the improved ideation performance themselves.

The second contribution is a Database of Design Cases (DOS) that are used as inspiration sources. DOS includes a database schema that supports the review of sources for the purpose of obtaining analogies. This is beneficial because novice designers tend to 1) inefficiently understand surface-level cues of design cases (Ball et al., 2004), and 2) collect partial design case information. All cases in DOS are classified and this classification data is used by PMGS, that in turn supports users to obtain in-depth understanding through increased visual stimuli (in Section 4.3.2). The schema was validated through population with 540 design cases and usage in the second stage of KEDIM. Use in this stage, 'Reviewing and evaluation by novice designers', supported by PMGS, confirmed that DOS improved the number of analogies used as inspiration. Discussion during experiments showed that some participants interpreted the case information incorrectly due to assumptions made regarding the images of the design cases. They noted this and amended it by reviewing the DOS outcomes. In this way, students iterated within the KEDIM process.

The third contribution is the visualisation method for the DOS outcomes, Perceptual Mapping Generation Software (PMGS). PMGS brings together selected design cases from the database and presents them in a way that enhances novice designers' abilities to draw analogies. PMGS contributes by providing a novel way of exploring and visualising large volumes of design cases and their detailed information in order to enhance drawing analogies based on the DOS outcomes. Perceptual mapping is a common method that has been widely used in the design field. PMGS offers a significantly faster working time to generate outcomes involving a large volume of cases (see Table 6.5) by using coding data from DOS to inform visualisation of detailed case data (see Section 4.3.2). These novel ways enhance novice designers' abilities to obtain and draw analogies from in-depth understanding of cases in DOS by providing opportunities for designers to explore a range of design cases. A number of authors report empirical research that confirms that the design case images and their information enhances designers' ability to draw analogies through increased stimulation (Goldschmidt and Smolkov, 2006; Goucher-Lambert and Cagan, 2017; Hua et al., 2019). However common perceptual mapping outcomes involve around 30 cases, because general methods do not provide the function for generation process. Accordingly, designers need to use a lot of working time for generation because of these limited functionalities of programs such as Adobe's illustrator (see Table 3.5). These issues identified the requirement for software that can decrease generation time so that the perception outcomes can involve a large volume of design case sources. The research results reported (in Section 4.3) established both the concept of PMGS and a novel way to deliver large amounts of information to users. In accordance with these issues identified, PMGS took less than 5 minutes to generate a perceptual map involving 540 cases (4,320 pieces of information with 8 pieces of information per case. See Figure 4.8). The coding system is a unique way to deliver visually detailed case information selected on case images together. An unexpected benefit also identified was that it clarifies the overall and specific properties of cases so that users can carry out more purposeful exploration of cases.

The fourth contribution is Systematic Brainstorming (SBI), where analogies are developed through a set of specific ideation themes alongside solution concepts. According to the number of ideas generated (one of the measurement metrics of ideation effectiveness by Shah (2003)), SBI users in the UK and Korea generated 22% and 85% more ideas (Table 6.6 and Figure 6.16) compared to control groups. In particular, the percentage of ideas according to a set of specific ideation themes (Figure 6.18.a) illustrates increased performance in ideation by experimental groups. Participants carried out breadth-first information searching at motif stage (Dinar et al., 2015), and identified valuable issues and opportunities during the following subsequent stages (Ho, 2001). Reviewing sketching outcomes (Figure 6.20) also showed the ideation development process through structured stages. Methods aiming to improve designers' idea generation processes heavily focus on improving users' unrestricted thought, however this might be unsuitable for the novice designers and can cause inefficient performance with greater confusion, because they conduct concurrent actions with vague objectives (Kavakli and Gero, 2002). In response to this critical limitation, SBI establishes a set of specific ideation themes based on the SECI theory which is a creative knowledge generation model by Nonaka et al., (2000), and a paper template for users to follow a set of specific ideation themes and guidelines. Evaluation experiments with 101 students in the UK and Korea confirmed that SBI enhances users' abilities for solution concept generation.

KEDIM, through these three stages, improves the effectiveness of novice designers' ideation from design brief to concept solution generation by increasing the number of concepts generated when compared with students not using KEDIM and responding to the same brief. KEDIM improved ideation performances through easy and intuitive usage followed by structured stages (reviewing sources, drawing analogies and generation of new ideas in Figure 2.5). The importance of good designs was highlighted as it has a positive impact on the life of end users, designers' effective working environment, and success of companies in response to societal issues in Chapter 1. Four contributions in this thesis support designers in order to successfully generate creative designs through the systematic three ideation stages.

7.2 Limitations of the research

This study represents a step to develop an ideation method in order to improve the ideation performance of novice designers. In the experiments and data analysis stages, three limitations were identified. Firstly, more detailed analysis of the assessment data collected could create opportunities to clarify development issues based on an in-depth understanding of participants ideation performance considering participants' ideation performance. The evaluation experiments were designed in order to obtain assessment data with diverse perspectives (Blessing and Chakrabarti, 2009), and they confirmed the contribution of KEDIM in accordance with research objectives. However, more detailed analysis of the data collected could be carried out. For instance, SBI was assessed by the comparative analysis of the number of ideas generated (quantity), although Shah (2003) provides four metrics (quantity, quality, variety, and novelty). Analysis of SBI through four metrics could yield greater in-depth understanding of users' ideation performance using SBI.

Secondly, the evaluation experiments were mainly designed to assess the use of KEDIM (DOS, PMGS, and SBI) at the initial development stage. Accordingly, two types of participant groups (the researcher, and design students) participated in the evaluation of the three tools of KEDIM. This data presents the validation of the effectiveness of the three tools of KEDIM, but is insufficient to analyse their correlation with respect of a systematic ideation process. For the further evaluation experiments, fixed participant groups who use all three tools of KEDIM together are required in order to perform a consistent assessment of components and KEDIM's process architecture.

Thirdly, intervention on the part of the participants' lecturers to provide feedback or have discussions during the experiments had not been considered at the development stage of research design. This led to variation across experiments that was seen to affect the participants' ideation performance (Figure 6.17), and as a result should be considered in future works. Although several limitations indicate potential variations, these should not detract from the effectiveness of KEDIM but suggest a further stage of future works.

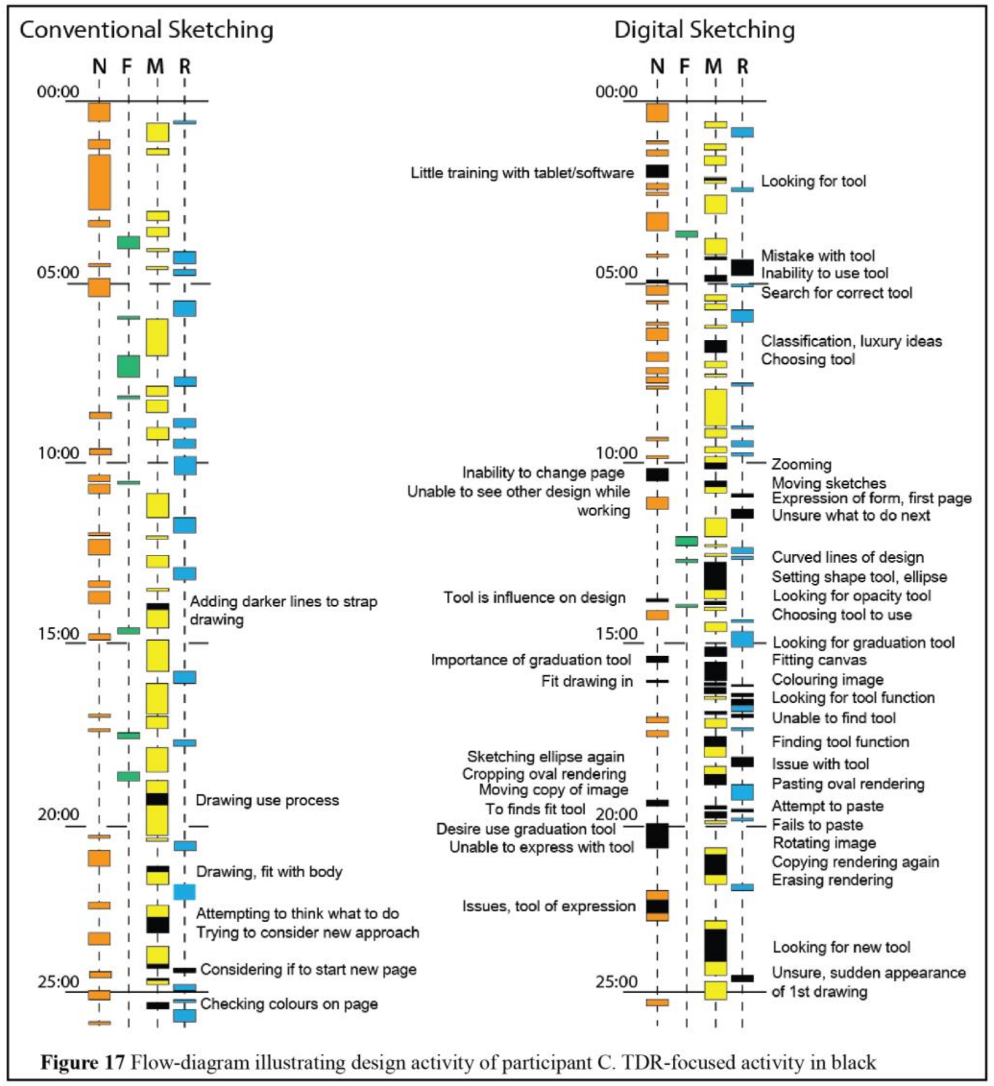
7.3 Future work

This section outlines work that could be carried out in response to the aforementioned limitations identified in Section 7.2, and, more widely, to expand across the creative ideation process and practice, and cognition in the short, medium, and long term. Additional evaluation tasks will be undertaken to generate more detailed data enabling schematisation of participant's ideation activities through coding of sketching outcomes and video recording that captures the ideation process. Figure 7.1 shows the examples by Self et al., (2016) and Dinar et al., (2015). The detailed assessment data gathered would provide the foundation to establish the two types of guidelines identified from the limiting issues emerging from experiments and data analysis. Firstly, the guidelines for lecturers will be established in response to the external variation identified (Figure 6.17) which influenced the degree of effectiveness of idea generation. Secondly, guidelines for the mixed methods of SBI and blank paper used during brainstorming will be constructed. This is as SBI was originally developed to replace the blank paper as a variation version, however, the participants of the individual experiment stated that its effectiveness varied according to the situation faced during ideation (Section 6.3.3). In addition, an update of Perceptual Mapping Generation Software (PMGS) will be implemented to provide extra information (coding definition, database name imported, and exported date and time) together on the outcome in order to improve user readability and understanding. After completing the aforementioned issues, evaluation experiments will be implemented with fixed participants who use all three tools together. It aims to collect consistent assessment of the three tools and their correlation in more detail.

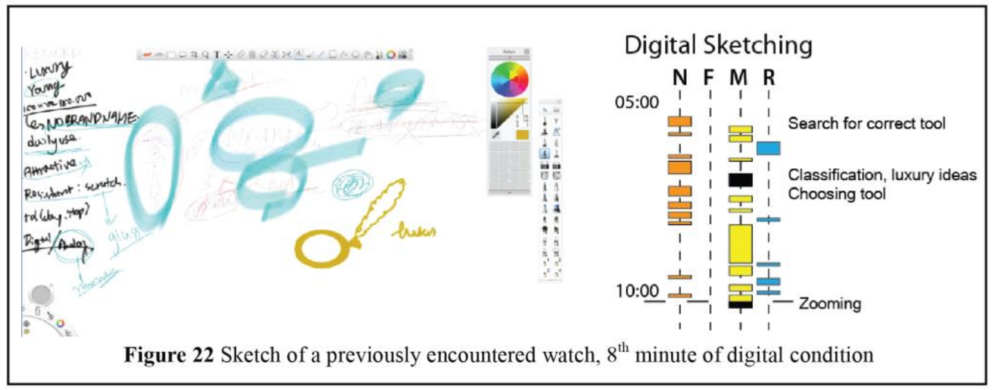
Based on these preliminary developments it is hoped that more attention towards the specialisation of the thesis across novice designers' creative ideation processes and practice based on understanding of their thought mechanisms. To achieve this aim, future works are established according to a timeline (short, medium, and long term). In the short term, DOS and PMGS (the first and second stages of KEDIM) could be elaborated using an approach such as Analysis of Exploratory Design ideation (AEDI) (Hay et al., (2019). Hay et al., (2019) identified two kinds of design ideation process: solution-focussed and exploratory. The solution-focused ideation process mainly generates diverse solutions in response to the brief. On the other hand, exploratory ideation refers to multiple interpretations of an open-ended problem/ tasks to create the associated solution (Hay et al., 2019). KEDIM falls into the first category, but DOS and PMGS support an exploratory ideation process in terms of populating a large volume of design case information as sources and their visualised exploration as open-ended tasks. Some evaluation data of DOS and PMGS (section 6.3.1 and 6.3.2) relied on the data gained from the researcher and the evaluation in perspective of novice designers. In this sense, AEDI (Hay et al., (2019) provides the systematic analysis method for DOS and PMGS in perspective of participants, and the analysed data will be used to elaborate their usage and functionalities.

For the medium term, visual stimuli and sketching will be researched in the context of SBI (third stage of KEDIM) development. SBI increases the number of ideas generated through a set of specific ideation themes. This process primarily involves users' interplay between internal (thought) and external representations (sketching and text) through visual stimuli. In this sense, Tedjosaputro et al., (2018) identified differences in the nature of interplay of coexistence between internal and external representations. Sketching and mental imagery support unique ideation, but it was highlighted that mental imagery increases quick idea generation and stimulation due to ease and speed, compare to sketching. This research result inspired the further development of SBI with the aim of involving the concept of mental imagery into systematic idea generation processes. Considering that the majority of methods do not provide this mental imagery stage during the ideation process, it is noteworthy that further versions of SBI provide a more elaborated process involving mental imagery stages that novice designers can follow. Hua et al., (2019) identified that combination of pictorial stimuli improves creative scores (quantity and variety by Shah et al., (2000)) compared to the other two groups (no stimuli and randomly presented pictorial stimuli in Google searches). The combination of stimuli arose as an important consideration in the development of SBI template in order to enhance novice designers' interaction between internal (mental) and external representation (pen and paper) through visual stimuli during form-generation process, which lies in the complex relationship of design object, motifs, and idea generation.

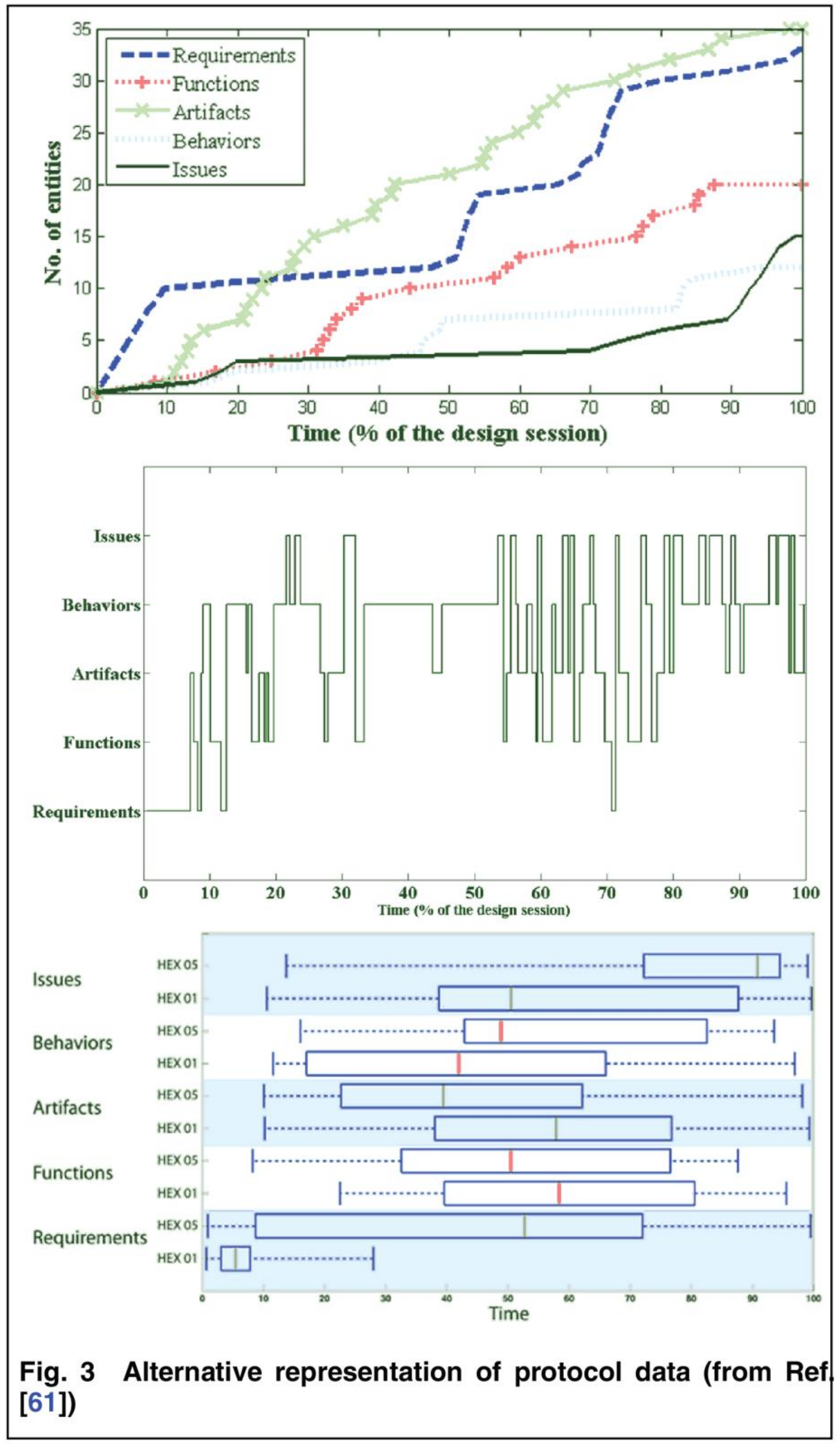
In the longer term, the research aims to enhance the creative ideation processes of novice designers: to exploit exciting opportunities from emerging manufacturing technologies into creative solution concepts through developing in-depth understanding and mitigation of fixations. From this perspective, Jablokow et al., (2019) made evident the diversity of designers' cognitive styles in team working environments and how this influences the number of discussion topics and the interconnectedness of those topics, based on an analysis of participants' ideation process through coding. It provides the importance of designers' cognitive styles in perspective of integrating new or unfamiliar technologies into ideation method development and evaluation.



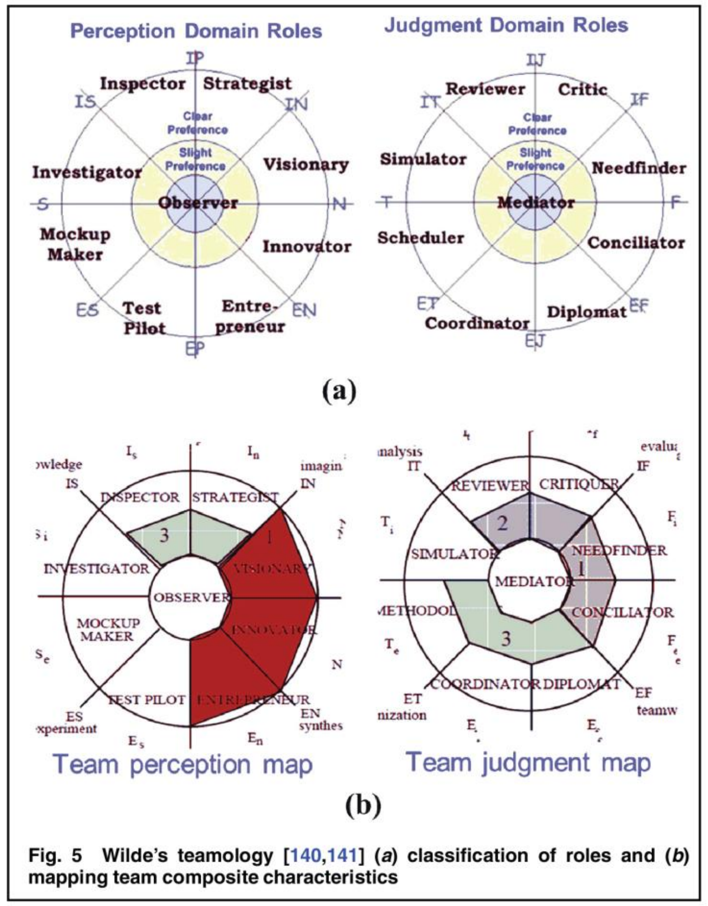
(a.1)



(a.2)



(b.1)



(b.2)

(a) Coding according to four objectives of idea (N: naming as problem analysis, F: framing as synthesis, M: moving as solution simulation, and R: reflecting as evaluation).

(b) Three versions of five types of participant attributes (requirements, functions, artefacts, behaviours, and issues).

Figure 7.1 Examples of further data analysis of designers ideation performance through coding. Source: (a) Self et al., 2016, and (b) Dinar et al., (2015)

7.4 Summary

This chapter has outlined the contribution and limitations of KEDIM to conclude evaluation data with respect to the research aim and objectives, and proposed future works for further development. The thesis aimed to propose an ideation method for novice designers' improved performance by mitigating the limitations identified from empirical research. This research has provided the analytical understanding of practical ideation approaches with a multi-dimensional consideration about common methods and their classification in order to identify the requirement to establish a solution concept. It identified the knowledge gap: empirical experiments have reported findings for the purpose of supporting creative solution concepts, but this has not been well applied to the ideation methods used by novice designers in education and practice. Its major cause is a difference of heterogeneity and difficulty associated with the method of usage, compared to the common methods they initially learned and used in education.

The thesis therefore established the ideation method, KEDIM, comprising variations of database, perceptual mapping, and brainstorming, to provide beneficial findings from empirical research through a systematic process, with an intuitive and easy method of use. Through analysis of evaluation data (sketching outcomes, description, questionnaire, observation, discussion, and self-report) it was evident that KEDIM contributes to improve novice designers' ideation performance based on findings from empirical research and experiments. It was apparent that KEDIM corresponds to requirements identified by novice designers: providing a structured ideation process, three tools enhancing improved performances, and its intuitive and easy use. During the process of evaluation experiments and data analysis, an unexpected issue arose (intervention from lecturer during workshop), and further detailed analysis of evaluation data and experiments were identified as the future works in order to improve the performance of KEDIM.

List of References

Ahmed, S., Wallace, K.M. and Blessing, L.T. 2003. Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*. [Online]. **14**(1), pp.1–11. Available from: http://link.springer.com/10.1007/s00163-002-0023-z.

Alberto, C. 2010. Design inspired by nature: from industrial revolution to the beginning 21 Century. [Accessed 1 January 2016]. Available from: http://bioinspired.sinet.ca/content/bio-inspired-design-landscape.

Anderson, C. 2012. *Makers: The new industrial revolution* 1st ed. New York: Crown Publishing Group.

Anthoniw, S. 2013. *Additive manufacturing: opportunities and constraints* [Online]. London. Available from: http://www.raeng.org.uk/publications/reports/additive-manufacturing.

Ball, L.J., Ormerod, T.C. and Morley, N.J. 2004. Spontaneous analogising in engineering design: a comparative analysis of experts and novices. *Design Studies*. [Online]. **25**(5), pp.495–508. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X04000353.

Ball, L.J., St.B.T. Evans, J., Dennis, I. and Ormerod, T.C. 1997. Problem-solving Strategies and Expertise in Engineering Design. *Thinking & Reasoning*. [Online]. **3**(4), pp.247–270. Available from: http://www.tandfonline.com/doi/abs/10.1080/135467897394284.

Blessing, L.T.M. and Chakrabarti, A. 2009. *DRM, a Design Research Methodology* [Online]. London: Springer London. Available from: http://link.springer.com/10.1007/978-1-84882-587-1.

Boden, M.A. 1998. Creativity and artificial intelligence. *Artificial Intelligence*. [Online]. **103**(1–2), pp.347–356. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0004370298000551.

Borgianni, Y., Lenarduzzi, V., Rotini, F. and Taibi, D. 2018. BRINGING STIMULATED IDEATION IN A WEB ENVIRONMENT : STUDENTS ' EVALUATIONS OF A BASIC SOFTWARE RELEASE *In*: Bath, pp.411–418. Available from: https://www.designsociety.org/publication/40731/BRINGING+STIMULATED+IDEATION+IN+A+WEB+ENVIRONMENT%3A+STUDENTS'+EVALUATIONS+OF+A+BASIC+SOFTWARE+RELEASE.

Bork, D., Karagiannis, D. and Hawryszkiewycz, I. 2017. Supporting Customized Design Thinking Using a Metamodel-based Approach Metamodel-based Approach for Customized Design Thinking Supporting Customized Design Thinking Using a Metamodel-based Approach. *20th Australasian Conference on Information Systems (ACIS) 2017*. [Online], pp.1–11. Available from: www.omilab.org.

Cai, H., Do, E.Y.L. and Zimring, C.M. 2010. Extended linkography and distance graph in design evaluation: an empirical study of the dual effects of inspiration sources in creative design. *Design Studies*. [Online]. **31**(2), pp.146–168. Available from: http://dx.doi.org/10.1016/j.destud.2009.12.003.

Cash, P.J. 2018. Developing theory-driven design research. *Design Studies*. [Online]. **56**, pp.84–119. Available from: https://doi.org/10.1016/j.destud.2018.03.002.

Chan, J., Fu, K., Schunn, C., Cagan, J., Wood, K. and Kotovsky, K. 2011. On the Benefits and Pitfalls of Analogies for Innovative Design: Ideation Performance Based on Analogical Distance, Commonness, and Modality of Examples. *Journal of Mechanical Design*. [Online]. **133**(8), p.081004. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?articleid=1450636.

Chootongchai, S. and Songkram, N. 2018. Design and Development of SECI and Moodle Online Learning Systems to Enhance Thinking and Innovation Skills for Higher Education Learners. *International Journal of Emerging Technologies in Learning (iJET)*. [Online]. **13**(03), p.154. Available from: http://online-journals.org/index.php/i-jet/article/view/7991.

Chuang, Y. and Chen, L.L. 2008. How to rate 100 visual stimuli efficiently. *International Journal of Design*. **2**(1), pp.31–43.

Cross, N. 2004. Expertise in design: An overview. *Design Studies*. **25**(5), pp.427–441.

Cross, N. 1999. Natural intelligence in design. *Design Studies*. [Online]. **20**(1), pp.25–39. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X9800026X.

Davis, J., Docherty, C.A. and Dowling, K. 2016. Design Thinking and Innovation: Synthesising Concepts of Knowledge Co-creation in Spaces of Professional Development. *Design Journal*. [Online]. **19**(1), pp.117–139. Available from: http://dx.doi.org/10.1080/14606925.2016.1109205.

Dennis, A.R., Valacich, J.S., Carte, T.A., Garfield, M.J., Haley, B.J. and Aronson, J.E. 1997. Research Report: The Effectiveness of Multiple Dialogues in Electronic Brainstorming. *Information Systems Research*. **8**(2), pp.203–211.

Dinar, M., Danielescu, A., MacLellan, C., Shah, J.J. and Langley, P. 2015. Problem Map: An Ontological Framework for a Computational Study of Problem Formulation in Engineering Design. *Journal of Computing and Information Science in Engineering*. [Online]. **15**(3), p.031007. Available from: http://computingengineering.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4030076.

Dinar, M., Shah, Jami., Cagan, J., Leifer, L., Linsey, J., Smith, S.M. and Hernandez, N.V. 2015. Empirical Studies of Designer Thinking: Past, Present, and Future. *Journal of Mechanical Design*. [Online]. **137**, p.021101. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4029025.

Dinar, M., Shah, Jami, Park, Y. and Langley, P. 2015. PATTERNS OF CREATIVE DESIGN: PREDICTING IDEATION FROM PROBLEM FORMULATION. , pp.1–10.

Dorst, K. 2011. The core of ‘design thinking’ and its application. *Design Studies*. [Online]. **32**(6), pp.521–532. Available from: http://dx.doi.org/10.1016/j.destud.2011.07.006.

Dorst, K. and Cross, N. 2001. Creativity in the design process: Co-evolution of problem-solution. *Design Studies*. **22**(5), pp.425–437.

Dugosh, K.L., Paulus, P.B., Roland, E.J. and Yang, H.-C. 2000. Cognitive stimulation in brainstorming. *Journal of Personality and Social Psychology*. [Online]. **79**(5), pp.722–735. Available from: http://doi.apa.org/getdoi.cfm?doi=10.1037/0022-3514.79.5.722.

El-Zanfaly, D. 2015. [I3] Imitation, Iteration and Improvisation: Embodied interaction in making and learning. *Design Studies*. [Online]. **41**, pp.79–109. Available from: http://dx.doi.org/10.1016/j.destud.2015.09.002.

Ericsson, K.A. 2002. Attaining Excellence Through Deliberate Practice: Insights from the Study of Expert Performance *In*: *Teaching and Learning* [Online]. Oxford, UK: Blackwell Publishers Ltd, pp.4–37. Available from: http://doi.wiley.com/10.1002/9780470690048.ch1.

Ericsson, K.A. 1999. Creative Expertise as Superior Reproducible Performance: Innovative and Flexible Aspects of Expert Performance. *Psychological Inquiry*. [Online]. **10**(4), pp.329–361. Available from: http://www.tandfonline.com/doi/abs/10.1207/S15327965PLI1004_5.

Farel, R. and Yannou, B. 2013. Bio-Inspired Ideation : Lessons From Teaching Design To Engineering Students. *ICED13: 19th International Conference on Engineering Design*. (August), pp.1–9.

Feng, T., Cheong, H. and Shu, L.H. 2014. Effects of Abstraction on Selecting Relevant Biological Phenomena for Biomimetic Design. *Journal of Mechanical Design*. [Online]. **136**(11), p.111111. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4028173.

Filippi, S. and Barattin, D. 2019. Influence of representations on shape-based design activities. *International Journal on Interactive Design and Manufacturing*. [Online]. **13**(1), pp.277–285. Available from: https://doi.org/10.1007/s12008-019-00534-1.

Fu, K., Moreno, D., Yang, M. and Wood, K.L. 2014. Bio-Inspired Design: An Overview Investigating Open Questions From the Broader Field of Design-by-Analogy. *Journal of Mechanical Design*. [Online]. **136**(11), p.111102. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4028289.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C.B., Wang, C.C.L., Shin, Y.C., Zhang, S. and Zavattieri, P.D. 2015. The status, challenges, and future of additive manufacturing in engineering. *CAD Computer Aided Design*. [Online]. **69**, pp.65–89. Available from: http://dx.doi.org/10.1016/j.cad.2015.04.001.

Gibson, I., Rosen, D. and Stucker, B. 2015. *Additive Manufacturing Technologies* [Online]. New York, NY: Springer New York. Available from: http://www.ciri.org.nz/nzrma/technologies.html.

Goldschmidt, G. and Sever, A.L. 2011. Inspiring design ideas with texts. *Design Studies*. [Online]. **32**(2), pp.139–155. Available from: http://dx.doi.org/10.1016/j.destud.2010.09.006.

Goldschmidt, G. and Smolkov, M. 2006. Variances in the impact of visual stimuli on design problem solving performance. *Design Studies*. [Online]. **27**(5), pp.549–569. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X06000172.

Goucher-Lambert, K. and Cagan, J. 2017. Using crowdsourcing to provide analogies for designer ideation in a cognitive study. *Proceedings of the International Conference on Engineering Design, ICED*. [Online]. **8**(DS87-8), pp.529–538. Available from: https://www.designsociety.org/publication/39871/Using+crowdsourcing+to+provide+analogies+for+designer+ideation+in+a+cognitive+study.

Gray, C.M., McKilligan, S., Daly, S.R., Seifert, C.M. and Gonzalez, R. 2019. Using creative exhaustion to foster idea generation. *International Journal of Technology and Design Education*. [Online]. **29**(1), pp.177–195. Available from: https://doi.org/10.1007/s10798-017-9435-y.

Hammer, M. and Mc Leod, D. 1981. Database description with SDM: a semantic database model. *ACM Transactions on Database Systems*. [Online]. **6**(3), pp.351–386. Available from: http://portal.acm.org/citation.cfm?doid=319587.319588.

Hay, L., Duffy, A.H.B., Grealy, M., Tahsiri, M., McTeague, C. and Vuletic, T. 2019. A novel systematic approach for analysing exploratory design ideation. *Journal of Engineering Design*. [Online]. **4828**, pp.1–23. Available from: https://doi.org/10.1080/09544828.2019.1662381.

Hernandez, N.V., Shah, J.J. and Smith, S.M. 2010. Understanding design ideation mechanisms through multilevel aligned empirical studies. *Design Studies*. [Online]. **31**(4), pp.382–410. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X1000027X.

Hey, J., Linsey, J., Agogino, A.M. and Wood, K.L. 2008. Analogies and Metaphors in Creative Design. *International Journal of Engineering Education*. [Online]. **24**(2), pp.283–294. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.161.4709&rep=rep1&type=pdf.

Ho, C.-H. 2001. Some phenomena of problem decomposition strategy for design thinking: differences between novices and experts. *Design Studies*. [Online]. **22**(1), pp.27–45. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X99000307.

Hopkinson, N., Hague, R. and Dickens, P. 2006. *Rapid manufacturing: an industrial revolution for the digital age*. West Sussex: john wiley and son.

Howard, T.J., Culley, S.J. and Dekoninck, E. 2008. Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies*. **29**(2), pp.160–180.

Hua, M., Han, J., Ma, X. and Childs, P. 2019. Exploring the Effect of Combinational Pictorial Stimuli on Creative Design Performance. *Proceedings of the Design Society: International Conference on Engineering Design*. **1**(1), pp.1763–1772.

Huo, K., Vinayak and Ramani, K. 2017. Window-Shaping: 3D Design Ideation by Creating on, Borrowing from, and Looking at the PhysicalWorld. *Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '17*. [Online]. (Figure 1), pp.37–45. Available from: http://dl.acm.org/citation.cfm?doid=3024969.3024995.

Jablokow, K.W., Sonalkar, N., Edelman, J., Mabogunje, A. and Leifer, L. 2019. Investigating the influence of designers' cognitive characteristics and interaction behaviors in design concept generation. *Journal of Mechanical Design, Transactions of the ASME*. **141**(9).

Jagtap, S. 2019. Design creativity: refined method for novelty assessment. *International Journal of Design Creativity and Innovation*. [Online]. **7**(1–2), pp.99–115. Available from: http://doi.org/10.1080/21650349.2018.1463176.

Jia, L., Becattini, N., Cascini, G. and Tan, R. 2020. Testing ideation performance on a large set of designers: effects of analogical distance. *International Journal of Design Creativity and Innovation*. [Online]. **8**(1), pp.31–45. Available from: https://doi.org/10.1080/21650349.2019.1618736.

Johnston, J. 2015. *Digital Handmade: craftmanship and the new industrial revolution.* London: Thames & Hudson.

Jonson, B. 2005. Design ideation: The conceptual sketch in the digital age. *Design Studies*. **26**(6), pp.613–624.

Kavakli, M. and Gero, J.S. 2002. The structure of concurrent cognitive actions: a case study on novice and expert designers. *Design Studies*. [Online]. **23**(1), pp.25–40. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X01000217.

Kim, T., McKay, A. and Thomas, B. 2019. A Systematic Brainstorming Ideation Method for Novice Designers based on SECI Theory. *Proceedings of the Design Society: International Conference on Engineering Design*. **1**(1), pp.249–258.

Knoll, S.W. and Horton, G. 2011. The impact of stimuli characteristics on the ideation process: An evaluation of the change of perspective ‘analogy’. *Proceedings of the Annual Hawaii International Conference on System Sciences*., pp.1–10.

Kokotovich, V. 2008. Problem analysis and thinking tools: an empirical study of non-hierarchical mind mapping. *Design Studies*. **29**(1), pp.49–69.

Koronis, G., Silva, A. and Kang, J. 2018. Impact of Design Briefs on Creativity : a Study on Measuring Student Designers Outcomes *In*:, pp.2461–2472. Available from: https://www.designsociety.org/publication/40767/IMPACT+OF+DESIGN+BRIEFS+ON+CREATIVE+OUTCOMES%3A+A+FACTORIAL+STUDY+ON+STUDENT+DESIGNERS%27+CREATIVITY.

Laing, S. and Masoodian, M. 2016. A study of the influence of visual imagery on graphic design ideation. *Design Studies*. **45**.

Laing, S. and Masoodian, M. 2015. A Study of the Role of Visual Information in Supporting Ideation in Graphic Design. *Communications in Information Literacy*. **3**(2), pp.80–90.

Langnau, L. 2016. Direct metal printing (DMP) enables CEEE to manufacture lean and green heat exchanger. . (March), pp.1–3. [Accessed 23 March 2016]. Available from: http://www.makepartsfast.com/2016/03/9328/metal-additive-manufacturing-enables-lean-green-heat-exchanger/.

Lauff, C.A., Perez, K.B., Camburn, B.A. and Wood, K.L. 2019. Design Principle Cards: Toolset to Support Innovations With Additive Manufacturing. , pp.1–15.

Lawson, B. 2006. *How designers think: The design process demystified* 1st ed. Oxford: Elishever / architectural.

Linsey, J.S., Clauss, E.F., Kurtoglu, T., Murphy, J.T., Wood, K.L. and Markman, A.B. 2011. An Experimental Study of Group Idea Generation Techniques: Understanding the Roles of Idea Representation and Viewing Methods. *Journal of Mechanical Design*. [Online]. **133**(3), p.031008. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?articleid=1449997.

Linsey, J.S., Markman, A.B. and Wood, K.L. 2012. Design by Analogy: A Study of the WordTree Method for Problem Re-Representation. *Journal of Mechanical Design*. [Online]. **134**(4), p.041009. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?articleid=1450796.

Madlener, A. 2011. What will it mean to be a designer in the future? *New realities, new roles for designers, Essay competition (Eindhoven: Design Academy Eindhoven)*. (April), pp.10–16.

Maher, M. Lou and De Silva Garza, A.G. 1997. Case-based reasoning in design. *IEEE Expert-Intelligent Systems and their Applications*. **12**(2), pp.34–41.

Maher, M.L., Poon, J. and Boulanger, S. 1996. Formalising Design Exploration as Co-evolution: A Combined Gene Approach. *Advances in Formal Design Methods for CAD: Proceedings of the IFIP WG5.2 Workshop on Formal Design Methods for Computer-Aided Design*., pp.3–30.

McLafferty, I. 2004. METHODOLOGICAL ISSUES IN NURSING RESEARCH Focus group interviews as a data collecting strategy. *Journal of advanced nursing*. [Online]. **48**(2), pp.187–194. Available from: http://ejournals.ebsco.com/direct.asp?ArticleID=4355BE29359F63694248.

Mohamad, N.A., Anwar, K., Khaidzir, M. and Ibrahim, R. 2016. A Study on Transforming the Knowledge in Design Learning Environment. . (August), pp.29–30.

Moreno, D., Blessing, L., Wood, K., Vögele, C. and Hernández, A. 2015. Creativity Predictors: Findings From Design-by-Analogy Ideation Methods' Learning and Performance *In*: *Volume 7: 27th International Conference on Design Theory and Methodology* [Online]. Boston, USA: ASME, V007T06A013. Available from: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?doi=10.1115/DETC2015-47929.

Moreno, D., Yang, M.C., Hernández, A.A., Linsey, J.S. and Wood, K.L. 2015. A Step Beyond to Overcome Design Fixation: A Design-by-Analogy Approach *In*: *Design Computing and Cognition '14* [Online]. Cham: Springer International Publishing, pp.607–624. Available from: http://link.springer.com/10.1007/978-94-017-9112-0.

Nelson, H.G. and Stolterman, E. 2014. *The Design Way: international change in an unpredictable world* 2nd ed. cambridge.

Nijstad, B.A. and Sroebe, W. 2006. How the Group Affects the Mind:A Cognitive Model of Idea Generation in Groups. *Personality and Social Psychology Review*. **10**(3), pp.186–213.

Nonaka, I., Toyama, R. and Konno, N. 2000. SECI, Ba and Leadership: a Unified Model of Dynamic Knowledge Creation. *Long Range Planning*. [Online]. **33**(1), pp.5–34. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0024630199001156.

Orthel, B.D. and Day, J.K. 2016. Processing Beyond Drawing: A Case Study Exploring Ideation for Teaching Design. *SAGE Open*. [Online]. **6**(3), pp.1–16. Available from: http://journals.sagepub.com/doi/10.1177/2158244016663285.

Ou, J., Dublon, G., Cheng, C.-Y., Heibeck, F., Willis, K. and Ishii, H. 2016. Cilllia: 3D Printed Micro-Pillar Structures for Surface Texture, Actuation and Sensing. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. [Online]. (c), pp.5753–5764. Available from: http://doi.acm.org/10.1145/2858036.2858257.

Papalambros, P.Y. 2008. Design innovation. *Journal of Mechanical Design, Transactions of the ASME*. **130**(4), pp.1–22.

Paulus, P.B., Kohn, N.W. and Arditti, L.E. 2011. Effects of Quantity and Quality Instructions on Brainstorming. *The Journal of Creative Behavior*. [Online]. **45**(1), pp.38–46. Available from: http://doi.wiley.com/10.1002/j.2162-6057.2011.tb01083.x.

Pearl, J. 2016. Comment : Understanding Simpson ' s Paradox Comment : Understanding Simpson ' s Paradox. . **1305**(January).

Piya, C., -, V., Chandrasegaran, S., Elmqvist, N. and Ramani, K. 2017. Co-3Deator: A Team-First Collaborative 3D Design Ideation Tool *In*: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17* [Online]. Denvor, pp.6581–6592. Available from: http://dl.acm.org/citation.cfm?doid=3025453.3025825.

Piya, C., Vinayak, Zhang, Y. and Ramani, K. 2016. RealFusion: An Interactive Workflow for Repurposing Real-World Objects towards Early-stage Creative Ideation *In*: *Graphic Interface Conference*. British Columbia, pp.85–92.

Prévost, R., Whiting, E., Lefebvre, S. and Sorkine-Hornung, O. 2013. Make It Stand: Balancing Shapes for 3D Fabrication. *ACM Trans. Graph.* [Online]. **32**(4), 81:1--81:10. Available from: http://doi.acm.org/10.1145/2461912.2461957.

Rabiee, F. 2004. Focus-group interview and data analysis. *Proc. Nutr. Soc.* [Online]. **63**(4), pp.655–660. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15831139%5Cnhttp://journals.cambridge.org/abstract_S0029665104000874%5Cnhref=%22http://dx.doi.org/10.1017/S0029665104000874.

Reinig, B.A. and Briggs, R.O. 2008. On The Relationship Between Idea-Quantity and Idea-Quality During Ideation. *Group Decision and Negotiation*. [Online]. **17**(5), pp.403–420. Available from: http://link.springer.com/10.1007/s10726-008-9105-2.

Romain, F. and Bernard, Y. 2013. Teaching Biologically Inspired Design to Engineers *In*: *19th International Conference on Engineering Design* [Online]. Available from: https://www.researchgate.net/publication/260752170.

Sakellariou, E., Karantinou, K. and Goffin, K. 2017. "Telling tales": Stories, metaphors and tacit knowledge at the fuzzy front-end of NPD. *Creativity and Innovation Management*. [Online]. **26**(4), pp.353–369. Available from: http://doi.wiley.com/10.1111/caim.12237.

Sarkar, P. and Chakrabarti, A. 2011. Assessing design creativity. *Design Studies*. [Online]. **32**(4), pp.348–383. Available from: http://dx.doi.org/10.1016/j.destud.2011.01.002.

Schön, D.A. 1983. *The Reflective Practitioner* [Online]. New York,: Routledge. Available from: https://www.taylorfrancis.com/books/9781315237473.

Schon, D.A. and Wiggins, G. 1992. Kinds of seeing and their functions in designing D. V. Nicolau, J. Enderlein, R. C. Leif, & D. L. Farkas, eds. *Design Studies*. [Online]. **13**(2), pp.135–156. Available from: http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.528071.

Sein, Henfridsson, Purao, Rossi and Lindgren 2011. Action Design Research. *MIS Quarterly*. [Online]. **35**(1), p.37. Available from: http://www.palgrave-journals.com/doifinder/10.1080/0268396022000017725.

Self, J.., Evans, M.. and Kim, E.J.. 2016. A comparison of digital and conventional sketching: Implications for conceptual design ideation. *Journal of Design Research*. [Online]. **14**(2), pp.171–202. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84975492129&partnerID=40&md5=0fb11d0f3244a1f7a96f438542992424.

Self, J. 2017. Resolving Wicked Problems: Appositional Reasoning and Sketch Representation. *Design Journal*. [Online]. **20**(3), pp.313–331. Available from: http://dx.doi.org/10.1080/14606925.2017.1301070.

Shah, J. 2003. Metrics for measuring ideation effectiveness. *Design Studies*. [Online]. **24**(2), pp.111–134. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X02000340.

Shah, J.J., Kulkarni, S. V. and Vargas-Hernandez, N. 2000. Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments. *Journal of Mechanical Design*. [Online]. **122**(4), p.377. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?articleid=1446075.

Simon, H.A. 1996. *The Science of the artificial* 3rd ed. London: The MIT Press.

Solomon, M.R. 2016. *Consumer behavior: buying, having and being* 12th ed. London, UK: Pearson.

Stones, C. and Cassidy, T. 2010. Seeing and discovering: How do student designers reinterpret sketches and digital marks during graphic design ideation? *Design Studies*. **31**(5), pp.439–460.

Tang, W., Hu, J., Zhang, H., Wu, P. and He, H. 2015. Kappa coefficient: a popular measure of rater agreement. *Shanghai Archives of Psychiatry*. **27**(1), pp.62–67.

Tedjosaputro, M.A., Shih, Y.T., Niblock, C. and Pradel, P. 2018. Interplay of Sketches and Mental Imagery in the Design Ideation Stage of Novice Designers. *Design Journal*. [Online]. **21**(1), pp.59–83. Available from: http://doi.org/10.1080/14606925.2018.1395655.

Töre Yargın, G., Moroşanu Firth, R. and Crilly, N. 2017. User requirements for analogical design support tools: Learning from practitioners of bio-inspired design. *Design Studies*. [Online]. **58**. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X1730090X.

Valkenburg, R. and Dorst, K. 1998. The reflective practice of design teams. *Design Studies*. [Online]. **19**(3), pp.249–271. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0142694X98000118.

Vasconcelos, L.A., Cardoso, C.C., Sääksjärvi, M., Chen, C.-C. and Crilly, N. 2017. Inspiration and Fixation: The Influences of Example Designs and System Properties in Idea Generation. *Journal of Mechanical Design*. [Online]. **139**(3), p.031101. Available from: http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4035540.

Venkataraman, S., Binyang, S., Jianxi, L., Karupppasamy, S., Elara, M.R., Blessing, L. and Wood, K. 2017. Investigating Effects of Stimuli on Ideation Outcomes *In*: *International Conference on Engineering Design (ICED17)* [Online]. Available from: https://www.researchgate.net/publication/316700510%0AInvestigating.

Ventola, L., Chiavazzo, E., Calignano, F., Manfredi, D. and Asinari, P. 2014. Heat Transfer Enhancement by Finned Heat Sinks with Micro-structured Roughness. *Journal of Physics: Conference Series*. [Online]. **494**(1), p.012009. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-84903643122&partnerID=tZOtx3y1.

Vincent, J.F. V, Bogatyreva, O.A., Bogatyrev, N.R., Bowyer, A. and Pahl, A.-K. 2006. Biomimetics: its practice and theory. *Journal of the Royal Society Interface*. [Online]. **3**, pp.471–82. Available from: http://rsif.royalsocietypublishing.org/content/3/9/471.

Wang, K., Nickerson, J. and Sakamoto, Y. 2018. Crowdsourced idea generation: The effect of exposure to an original idea. *Creativity and Innovation Management*. **27**(2), pp.196–208.

Whelan, L., Maher, C. and Deevy, C. 2017. Towards a University Design School. Restoring the value of tacit knowledge through assessment. *The Design Journal*. [Online]. **20**(sup1), pp.S1459–S1470. Available from: http://doi.org/10.1080/14606925.2017.1352670.

Wilson, J.O., Rosen, D., Nelson, B.A. and Yen, J. 2010. The effects of biological examples in idea generation. *Design Studies*. [Online]. **31**(2), pp.169–186. Available from: http://dx.doi.org/10.1016/j.destud.2009.10.003.

Wiltschnig, S., Christensen, B.T. and Ball, L.J. 2013. Collaborative problem-solution co-evolution in creative design. *Design Studies*. [Online]. **34**(5), pp.515–542. Available from: http://dx.doi.org/10.1016/j.destud.2013.01.002.

Yang, M.C. 2003. Concept generation and sketching: Correlations with design outcome. *Proceedings of the ASME Design Engineering Technical Conference*. **3**, pp.829–834.

Appendices

SBI evaluation data from Korean participants was presented to the Korea Society of Design Science(KSDS) 2018 Fall International Conference (Appendix A) and Invitation Exhibition (Appendix B) in order to introduce SBI in Korea. The information and presented material are provided in detail in sequential sections.

Appendix A: A Poster for Korea Society of Design Science (KSDS) International Conference 2018

This poster was presented at Tongmyong University (Busan, South Korea) on 3rd November 2018. For detailed information, please see the following title, abstract, and poster.

Title: Improving novice designers’ design ideation processes: a systematic brainstorming method based on the SECI theory

Abstract

Ideation, which aims to generate novel or creative solutions, is one of the most unique yet required abilities of designers. In actual design ideation works, the brainstorming method has been frequently and traditionally used with the aim of generating quantitative idea elements through cognitive stimulation. The capability to freely express and develop the memory, information, and thought by the designer’s intuitive abilities is the main benefit of brainstorming, but on the other hand, this characteristically includes an unsystematic process and tends to rely on personal abilities for ideation.

With the aim of remedying these limitations, this work develops the Systematic Brainstorming Ideation paper template (SBI) based on the SECI theory, which is a knowledge creation model with repeated cycles between tacit and explicit actions.
SBI consists of five separate sections in order to suggest specific ideation themes.

To evaluate SBI, experimental research was conducted with 71 novice designers during one hour’s ideation. The results indicate that the number of generated idea elements per person by the experimental group with SBI (11.3) was nearly 50% more compared to the control group with blank paper (7.4). Moreover, this quantitative difference seems to be the major finding of the comparative analysis results; the experimental group used richer methods of expression (sketch and text) and explored more diverse themes compared to the control group.

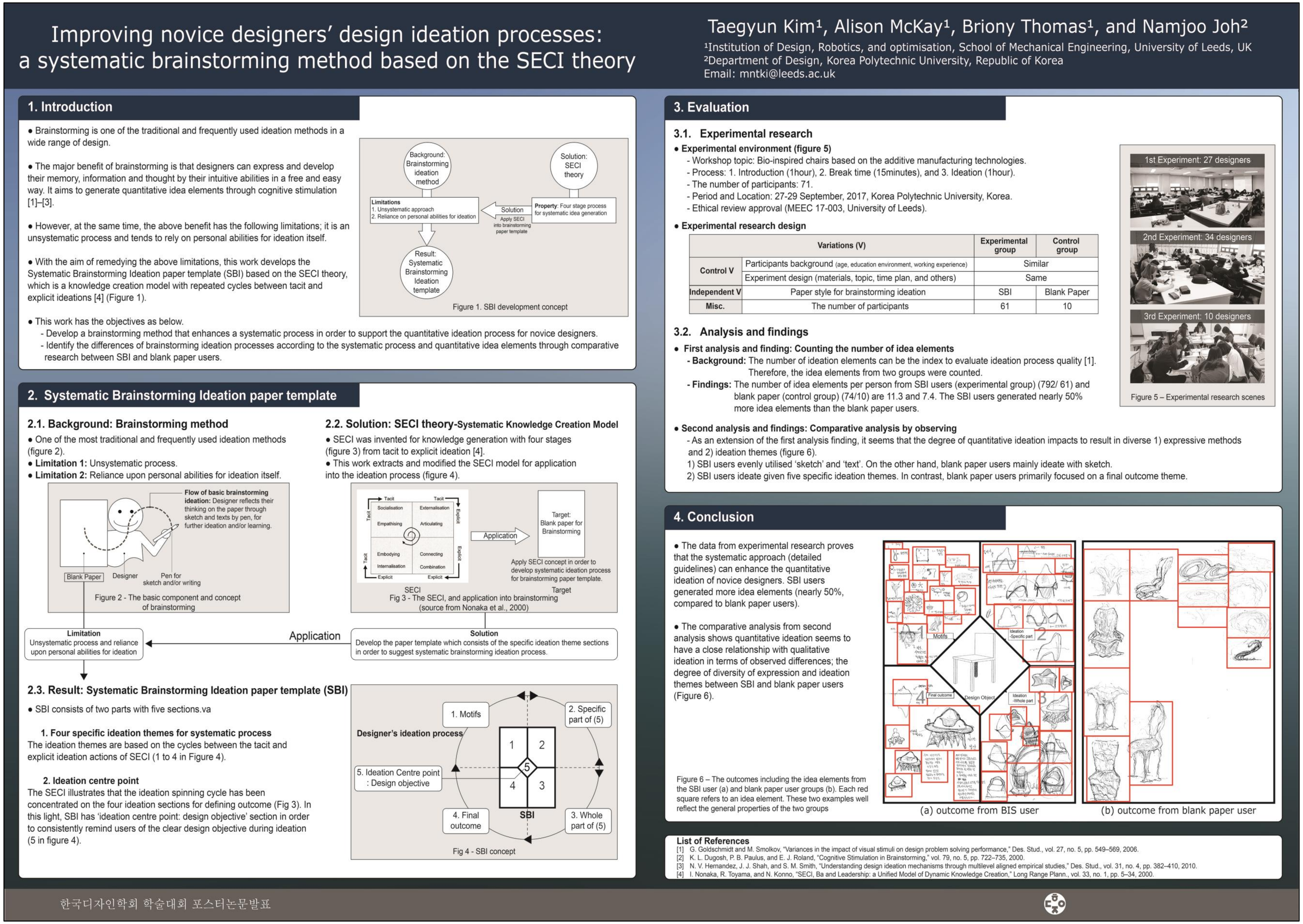


Figure Appendix A1. Poster for KSDS 2018 Fall International Conference (original size: A1)

Appendix B: Work for Korea Society of Design Science (KSDS) 2018 Invitation Exhibition

The sketching outcomes from Korean participants were translated in order to visualise complex ideation by 71 participants. This work was submitted to KSDS 2018 Invitation Exhibition, and displayed at Tongmyong University (Busan, South Korea) for 1 week (3^{rd} to 12^{th} November 2018). For detailed information, please see the following title, explanation, and poster.

Title: Metaphorical Shape of Ideation: An Exploratory Study

Explanation: Design ideation has been viewed as atypical and nearly impossible to visualise, yet it is the most unique and important role of designers and researchers. This work (the metaphorical shape of ideation flow) shows in essence the result of an exploratory study. 71 designers conducted brainstorming with paper templates, separated into five ideation stages, and the collected outcomes were overlapped to formalise their ideations. As a result, this work defines a clearer image of ideation as a metaphor in order to present vision and motivations, and the challenges facing designers such as unknown areas that researchers need to explore.

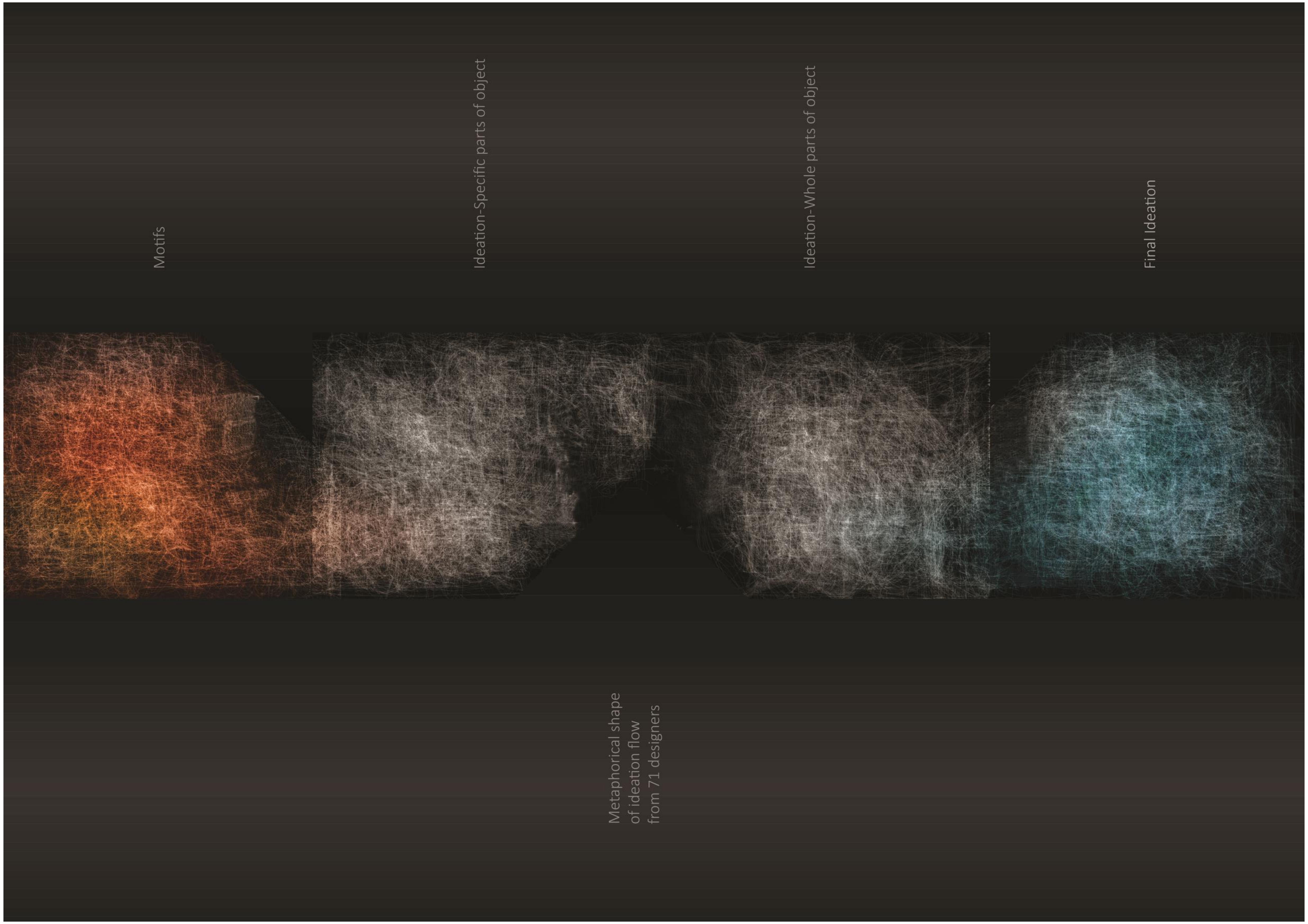


Figure Appendix B1. Work for KSDS 2018 Fall International Invitation Exhibition (original size: A1 and landscape)