Analogical Creative Thinking and Its Application to Engineering Design and Enterprise

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Abstract

Analogical thinking is valuable to creative design as it assists generation of new knowledge by mapping analogically from source domain to target domain. This study endeavours to enhance the value of analogical thinking in creative design by the development of Analogical Creative Process (ACP), and evaluation of its application in projects of engineering design and enterprise design. ACP is a systematic step-by-step tool to enable analogical thinking in design, and is derived from the fundamental cognitive process of key theories for analogy establishment. It analyses the given design problem as a complex of sub-systems and identifies their functions, before analogically mapping over the relations among the sub-systems between different domains. With these features, ACP is capable of providing tangible guidance on analogical thinking for designers without requirement of their existing experience in use of analogy. The effectiveness of ACP in creative ideation is examined with positive outcome observed in a real-life engineering design project compared to non-analogical approaches.

The interrelations between creativity, analogy and design are identified featuring ACP and analogical thinking through a prescriptive study. As a result, a novel analogy-empowered creative design process is proposed and applied in an enterprise design project as a new field of application for analogical thinking in design. Initial evaluation supports the application success of the creative design process and analogical thinking is proven valuable in assisting enterprise design practices.

The outcomes of this study include development of ACP based on the cognitive model of analogy, establishment of a new connection between creativity, analogy and design by the analogy-embedded creative design process, and a new design application of analogical thinking in enterprise. The identification of the value of analogical thinking in the context of enterprise design provides the researchers and entrepreneurs with a new tool to enhance enterprise design and business progress.

Declaration of Originality

Except otherwise where stated, the research work reported in this thesis is my own. All efforts are made to ensure other researchers' work in this thesis are properly referenced. This research was conducted in Dyson School of Design Engineering, Imperial College London with the aim of the degree of Doctor of Philosophy, and has not been submitted as consideration for any other degree at any other institute of learning.

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Copyright Declaration

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Chapter 1. Introduction to the study and the thesis

This chapter provides a general introduction to the study and the thesis. The scope and structure of this research are briefly discussed, together with the overall research strategy and motivation, with engineering design and enterprise as application fields for analogical thinking. Principal questions for each chapter to address are illustrated to indicate the flow of study, and key study activities are highlighted chapter by chapter as part of the introduction.

1.1. Introduction to the study

This study is on human creativity, and specifically on analogy and its value in the enhancement of human creativity in the context of design. It endeavours to utilise analogical thinking to improve the creative output in design. This study

- identifies the existence of analogy in creativity;
- analyses the essence of analogy through its definition, establishment and presentation;
- investigates the value of analogy in creative ideation in engineering design, where creativity plays an important role;
- explores the approach to integrating analogical thinking into creative design on a theoretical level; and
- evaluates the applicability and initial success of such approach through the application in a real-world enterprise design project.

The aim of this research study is to answer the following questions:

- Is analogy of value in enhancing human creativity?
- What practical approaches could analogy be applied to assist real-world engineering design activities?
- What is a possible model through which analogy is capable of benefiting the design of enterprise in practice?

Human creativity is inseparably associated with human civilisation and development and is reflected in all areas of study such as arts, humanities, sciences and technology. As it is impossible and impractical to study every area where creativity is involved, this study concentrates on creativity in engineering design and enterprise design, with the spirit of entrepreneurship and real-life application.

This study includes theoretical reviews of literature on both creativity and analogy, as well as a practical exploration of the application of analogy in real-world projects of engineering design and the design of enterprise. With insights into the added value of analogy established by literature review and reasoning, analogical thinking has been subsequently applied to real-world projects of engineering design and enterprise design, where exploratory studies were carried out endeavouring to realise the value of analogy in practical applications with different criteria and requirements. The structure of this research is illustrated in Figure 1.1.

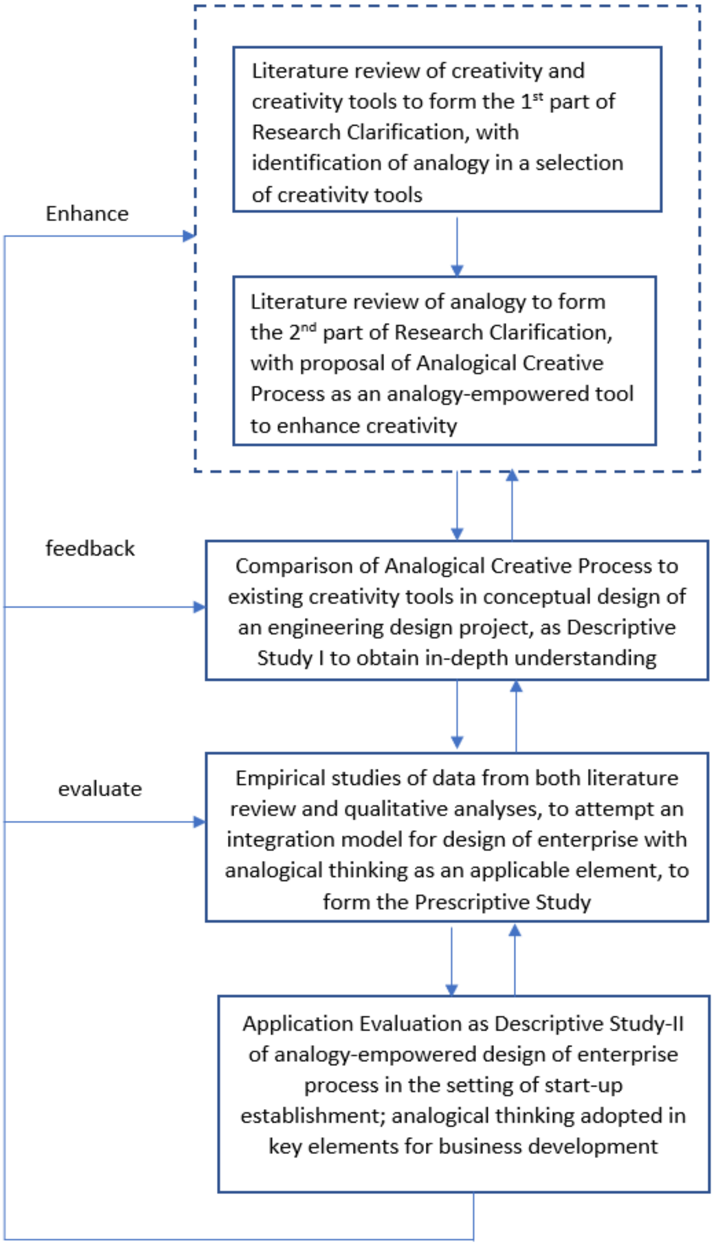


Figure 1.1. Structure of research

1.2. Research motivation and scope

1.2.1. Research motivation and background

This study endeavours to enhance human creativity by application of analogical thinking in the context of design. Creativity has been widely investigated in research fields including cognitive science, psychology, art, education, and design (see Section 2.1). Analogical thinking is considered valuable in enhancing human creativity and identifiable in typical creativity tools including TRIZ, Synectics and Biomimetics (see Section 3.4). Inspired by relevant literature review and the researcher's observation and reasoning, this study expects a more systematic method derived from analogical thinking, and such outcomes have been identifiable through application in a series of case studies.

This study is also motivated by the researcher's personal experience and observation of the value of analogical thinking in general. Through growing up, and an education background, in China, the researcher has access to all aspects of traditional Chinese culture including philosophy, history and art. Analogical and metaphorical elements are commonly identifiable in these fields and play an effective role in communication and creation. It would be interesting and potentially valuable to explore explicit methods involving analogical thinking, given the observation that analogy's common existence in the more abstract-oriented Eastern cultures.

The research and application development of Design by Analogy (DbA) and metaphorical design suggests that design could benefit from analogical thinking. Both analogy and metaphor function by establishing mapping between a more familiar source domain and a less familiar target domain, in order to gain better understanding of the less familiar (Gentner, 1989). However, analogy is distinguished from metaphor in respect of the elements being mapped over; analogy and metaphor also differ in the primary function within the design process, as well as the stage of existence (Hey et al., 2008). This comparison further coincides with the observation where students studying architecture have applied metaphor as a tool in situation defining and design problem framing at early design stage (Casakin, 2006). With external text stimulation, the increased use of metaphors also contributes to discussing and communicating design solutions (Casakin, 2017). The identification of such differences in design realm echoes with the characteristics difference between analogy and metaphor in cognitive research, which indicates that analogy is primarily more concerned with mapping of relations and structure, while metaphorically mapping would include elements from both relation and attribute (see Section 3.2).

1.2.2. Research scope

This study endeavours to explore the value of analogical thinking as a method, in the context of creative design. In order to not only evidence the validity of the method developed, but also increase its applicability and adaptability, it is deemed essential to investigate more than single designs fields for study of application. Descriptive studies are implemented through case studies of both engineering design and enterprise design as research scope, regulated by the overall research rationale of exploring the value of analogical thinking in the context of engineering design and enterprise.

Engineering design, as a well-studied design field to apply analogy and analogical thinking (Dahl and Moreau, 2002, Christensen and Schunn, 2007, Gassmann, 2008), provides rich evidence of value and thus is suitable to explore further in order to obtain in-depth understanding (see Section 6.4). In addition, the access that the researcher has to the resources of engineering designers and engineering design projects increases the research validity.

Following the process of the chosen overall research methodology and, in order to study and develop analogical thinking as a method, a totally different application realm of enterprise design has been selected to further evaluate the applicability of analogical thinking. The term "Design of enterprise" indicates not only enterprise as the objective and deliverable of design activities, also the design process towards establishment of enterprise involving design methods such as analogical thinking. Enterprises foster creativity and innovation, thus create significant impact towards sustainability of economy and society. In particular, this study explores analogical thinking in entrepreneurship within the context of Small and Medium Enterprises (SMEs) to seek increased impact, because SMEs in the UK count for over 99.9% of the total quantity of businesses, and provide approximately 60% of the total employment (Rhodes, 2018). Therefore, the findings on the creative design of enterprise with analogical thinking would be expected to increase both academic and economic impact (see Section 7.1). The consistency observed on the value of analogical thinking in both engineering design and enterprise design would further make sense of the overall research rationale.

1.3. Introduction to the thesis

1.3.1. Overview of thesis structure

This thesis is structured as follows. It begins with a literature review of human creativity, creativity tools and analogy, and then moves on to introduce the research methods and approaches. Subsequently, the thesis identifies and analyses analogical thinking in creative ideation to gain fundamental insights into analogy from an engineering design project. The study of analogical thinking in the design of enterprise on both a theoretical and an application level are recorded in chapters 7 and 8, where different approaches are adopted to examine the value of analogy with new knowledge being developed in an environment of entrepreneurship and innovation. A more detailed introduction to each chapter is described below.

This thesis is structured so as to address the principal questions listed in Table 1.1.

Chapter	Principal question addressed
1	What is the study about and how is the thesis structured?
2	What are creativity tools and their functionality?
3	What is analogy? How is it established and how can it be used as a creativity tool?
4	What are the strategy and methodologies of this study?
5	What is a possible form of systematic analogical thinking method like?
6	What is the value of analogical thinking in conceptual ideation of an engineering design project?
7	Can analogical thinking contribute to the development of enterprise both in theory and in reality?
8	How to enhance key development of a start-up enterprise using analogical thinking?
9	What are the conclusions of this study?

Table 1.1. Principal questions to address in each chapter

These questions drive the study activities through the research process progressively and consistently. Principal questions for Chapters 1 and 4 provide a framework of how the study is initiated, organised and conducted. Principal questions for Chapters 2 and 3 lay down the foundation for the study and set boundaries within the realms of creativity, analogy and design. These questions arose from the literature review of creativity and analogy, and are described in detail in sections 2.3 and 3.4, respectively. The aims of chapters 5, 6, 7 and 8 are within the regulation of research methodology framework organised in Chapter 4. These questions aim to explore a possible form for systematic analogical thinking method (Chapter 5), in-depth the application of analogical thinking in engineering design (Chapter 6), the possible support of an analogy-empowered creative design process developed through prescriptive study (Chapter 7), and further evaluation of analogical thinking in the design of enterprise (Chapter 8).

1.3.2. Review of creativity and creativity tools in Chapter 2

Chapter 2 reports a strategic and concise literature review of human creativity and creativity tools. Creativity tools, or creativity techniques, are the techniques used to enhance users' creativity, and are derived from numerous experiences of applications to enhance both divergent and convergent creative thinking phases, reflecting certain aspects of creative thinking (e.g. lateral thinking, analogical thinking). A detailed review of the classification of the mainstream creativity tools is recorded to provide a more straightforward understanding of how creativity tools function. A selection of typical creativity tools is subsequently investigated in greater detail in order to identify their essence of functionality. It is at this stage that analogy has been identified as the core of several creativity tools. It is suggested that further research on analogy is necessary as a direction which could lead to a potential enhancement of human creativity.

1.3.3. Review of analogy in Chapter 3

Chapter 3 reviews the definitions and theories of analogy, in order to gain an in-depth understanding of analogy. Both Structure Mapping Theory and Multiconstraint Theory are able to systematically explain the establishment of analogy. However, since these theories are primarily focused on the principles of analogy, none of them have provided clear practical instructions on how to take advantage of analogy to enhance creativity, especially in the domain of design engineering. The review of other literature on analogy has indicated that the essence of analogy exists in a group of creativity tools such as TRIZ, Synectics, and Biomimetics.

1.3.4. Research strategy and methodology in Chapter 4

The strategic aim of this study is to promote analogical thinking in creative design, through an exploration of the possible forms to present and apply analogical thinking. The contribution from this study also includes the development and evaluation of an analogy-empowered creative design process, the applicability of which is evaluated in the context of enterprise design. The strategy is to increase the angles of the investigation to analogical thinking under the different settings of requirements, so that the outcome could be more comprehensive. The case study in engineering design compares the ideation outcome of non-analogical and analogical approaches, in order to understand the value of analogical thinking in conceptual design ideation. A further application of analogical thinking in enterprise design provides applicability evaluation for the proposed analogy-empowered creative design process in the enterprise context.

Empirical studies have been adopted in real-world case studies to test the value of analogical thinking. In order to combine the advantages of qualitative and quantitative studies, a methodology of Mixed Method Research (MMR) has been primarily adopted for the study, where a preliminary conclusion could be reached from triangulation.

1.3.5. Development of ACP as a method for analogical thinking in design in Chapter 5

Based on the literature review on creativity and analogy, while no discovery has been identified with analogy solely as a systematic creativity tool, let alone there being any further research on the creativity tool of systematic use of analogy in real-world design projects. To address these gaps in research, Analogical Creative Process (ACP) has been developed to examine the primary value of analogy in creative design activities.

The value of analogical thinking is examined at a later stage, through design projects of engineering design and enterprise design.

1.3.6. Application of analogy in a product design project in Chapter 6

Following the understanding reached by the literature review on creativity and analogy, Chapter 6 explores the value of analogical thinking in the conceptual design ideation of an engineering design project. Under a controlled environment with clear information on requirements and restrictions, a group of thinkers work on creative ideation using both non-analogical creativity tools and analogical approaches. Qualitative methods have been primarily adopted to evaluate the outcome of these creativity tools in comparison. As part of the Mixed Method Research, feedback from participants is collected by interviews to understand their ideation process in a more comprehensive manner. This study attempts to identify the value of analogical thinking in the creative ideation for conceptual design, through the comparison with outcomes from non-analogical creativity tools.

1.3.7. Identification of analogy in the development of existing enterprises in Chapter 7

Chapter 7 endeavours to develop research support in theory for the application of analogical thinking in creative design. An analogy-empowered creative design process has been developed based on a new angle of connection identified between creativity, design and analogy. The process uses analogical thinking as the principal approach, with integration of divergent-convergent thinking, human-centred element of empathy and a comprehensive structure of design process.

The analogy-empowered creative design process is meant to be applicable in the design of enterprise. Analogies have been identified consistently within the public speeches by well-known business leaders, as well as interviews to a selection of enterprises featuring start-up companies. The research developed by Chapter 7 indicates the possible value of analogical thinking in the realm of enterprise design, with necessary further evaluation.

1.3.8. Application of analogy in an enterprise design project of a start-up business in Chapter 8

Chapter 8 aims to initially evaluate the applicability of research support developed previously, by adopting a practical approach to realise the value of analogical thinking in a case study of design of enterprise. Embedded into an analogy-empowered creative design process, analogical thinking as a tool for strategic planning has been applied in key phases including the identification of market requirements, the advancement of technology and the development of business models. Analogical thinking has been found to be successful in assisting the establishment of a start-up company and all of its three key phases.

The start-up company has been selected as an innovative enterprise and invited to the annual Wuxi Summit of Talents and Innovation in China 2019. Experts in entrepreneurship and the public gave the company a positive evaluation in technology adaption and business model, where analogical thinking has been applied to enhance the design of the company.

1.3.9. Conclusion in Chapter 9

Chapter 9 summarises the roadmap of this study on analogical thinking and its value in the enhancement of creativity, from application in engineering design and enterprise design. Findings from this study are discussed and contributions to knowledge with the impacts of this study are also identified. The conclusions of this study are revealed in accordance with the structure of research in Figure 1.1. Possible directions for future research are also identified in Chapter 9.

Chapter 2. Review of creativity and creativity tools

The literature review of creativity and creativity tools in this chapter lays the foundation for this study as the starting point. In order to identify possible research gaps and progress towards new applications or connections, a considerable level of key understanding of the findings from the existing research on creativity needs to be established. The literature review of creativity and creativity tools aims to provide the researcher with updated strategic knowledge of this research field, and potentially shapes the direction for elaborated studies for focused research activities. The review of a selection of creativity tools enriches the understanding of creativity in application, and relates to the use of certain reviewed tools in the subsequent chapters.

2.1. Review of Creativity and Creative Problem Solving (CPS)

The strategic literature review of creativity endeavours to balance between the scope and the depth of review findings. Creativity is a vast research field and the research topic of creativity requires overall knowledge and insightful understanding. The review strategy involves gathering answers to symbolic questions such as: a) what is the aim of the reviewed research? b) why and how have the researchers conducted such research activities? c) what are the key findings from the reviewed research? d) what quality does the reviewed research demonstrate? With these review objectives in mind, the researcher tends to start reviewing an article by reading the abstract, and then proceeds to introduction and conclusions to gain a holistic understanding. Should the research be deemed relevant and quality, then extra attention is paid when reviewing the research methods, results and findings. A review would be terminated if its research topic is irrelevant to the study. This strategy is adopted to all literature review activities for this study to support subsequent study activities.

The strategic literature review also entails that additional attention is given to research findings with significant meaning for this study. For instance, review of Creative Problem Solving and Brainstorming is conducted and reported in greater details, because they are important research topics with rich research interests and findings, and relate to the production of new findings (see Chapter 7 for Creative Problem Solving and Section 6.3 for Brainstorming). The enhanced review of such topics would not only increase the researcher and reader's understanding of the research field, but would also effectively connect the existing findings to potential new developments.

2.1.1. Review of Creativity

Creativity can be defined as the act of making new relationships from old ideas (Schlesinger, 1980), the ability to look at things differently (Oneill, 1990), or as an act that produces effective surprise (Curry, 1972), or as the ability to imagine or invent something new of value (Childs, 2006). Creativity is defined in the Random House Webster's College Dictionary as "The state or quality of being creative; the ability to transcend traditional ideas, rules, patterns, relationships, or the like, and to create meaningful new ideas, forms, methods, interpretations, etc.; Originality; progressiveness, or imagination; the process by which one utilizes creative ability" (Dictionary, 2001). Among all the definitions of creativity, as Thompson and Lordan have pointed out and agree (Thompson, 1999), the most common characteristics of creativity are considered to be newness (uniqueness) and value (utility) (Cougar, 1993). Systematic research on creativity is deemed to begin as early as Glaton's studying of genius in 1869 (Craft, 2001). Creativity has great impact on our lives (Robinson, 2008) and, as we are living in an ever-changing world with new technologies blossoming, "creativity is a useful and effective response to evolutionary changes" (Runco, 2004, p.657). As pointed out and analysed in detail, the "standard definition" of creativity was brought into from and indicates that creativity requires both originality and effectiveness (Stein, 1953). Table 2.1 illustrates the definition of creativity provided by selection of dictionaries in English, and the definition coincides with what appear to be the key attributes of creativity: novelty and usefulness.

Dictionary	Definition	Source
Collins Dictionary	Creativity ability; artistic or intellectual inventiveness.	http://www.collinsdictionary.com/dictionary/english/creativity last accessed on Jul 15 2019
Oxford English Dictionary (OED)	The faculty of being creative; ability or power to create.	http://www.oed.com/view/Entry/44075?redirectedFrom=creativity& last accessed on Jul 15 2019
Oxford Dictionary of English	The use of imagination or original ideas to create something; inventiveness.	https://en.oxforddictionaries.com/definition/creativity last accessed on Jul 15 2019
Merriam-Webster Dictionary	The quality of being creative; the ability to create.	http://www.merriam-webster.com/dictionary/creativity last accessed on Jul 15 2019
Longman Dictionary of Contemporary English	The ability to use your imagination to produce new ideas, make things etc.	http://www.ldoceonline.com/dictionary/creativity last accessed on Jul 15 2019

Table 2.1. Meanings and explanations of creativity in major English dictionaries

Creativity is broadly defined as the ability to create meaningful new ideas, form, sounds, methods, performances, and interpretations. A further operational definition is given as “the particular actions of consciously operating knowledge through some reasoning to generate a design idea that has a certain functional, aesthetic, and marketable value; and that resulting production is new, novel, beautiful, and accepted by public” (Chan, 2015, p.262). This definition combines the elements of problem solving and generating novelty, and is built upon previous research on attempts to define creativity. Typical definitions for creativity from different approaches are adapted in Table 2.2 (Taylor, 1988). This study as a whole would like to explore analogy-empowered creativity and its new way of application in the design process of enterprise; therefore, it is the design and problem-solving related defining approaches that will be more relevant to comprehending creativity.

Source	Defining approach	Definition
(Wertheimer, 1959, p.31)	Perception related	“The process of destroying one gestalt in favour of a better one.”
(Stein, 1953, p.312)	Process related	“The process which results in a novel work that is accepted as tenable or useful or satisfying by a group at some point in time.”
(Torrance, 1975)	Process related	The process of sensing difficulties, problems, gaps in information, missing elements, something askew, and testing these guesses and hypotheses; possibly revising and retesting them; and finally communicating the results.
(Ghiselin, 1955)	Expression related	The process of change, of development, of evolution in the organisation of subjective life.
(Kubie, 1977)	Personality related	Creativity is defined in terms of interactional strength ratios of the identity, personal ego, and superego.
(Guilford, 1959)	solution related	The ability to develop information out of what is given by stimulation.
(Amabile, 1983b)	Response related	A response that 1) It is both a novel and appropriate, useful, correct, or valuable response to the task in hand; and 2) The task is heuristic rather than algorithmic.
(Csikszentmihalyi, 1996)	Social and cultural domains	Any at, idea, or product that changes an existing domain, or that transforms an existing domain into a new one.
(Torrance, 1969)	Problem solving related	The ability for generation of original ideas, developing a different point of view, breaking out of the mould, recombining

		ideas, or seeing new relationships among ideas.
(Sternberg, 1985)	Domains of physics and art	Creativity in physics is described by inventiveness and orderliness, and creativity in art is represented by imagination and originality.
(Coyne, 1997)	Design related	A human faculty that exceeds the everyday and routine process of thinking and doing.
(Eckert et al., 2012)	Design related	The act of creating something new, a new insight, a new theory or a novel design.
(Kazerounian and Foley, 2007)	Design related	The ability to generate new ideas or new association between existing ideas. The ability to make new things.
(Doboli and Umbarkar, 2014)	Design related	Creativity is often characterized by referring to the novelty (e.g., solutions have less frequent features) and utility (i.e. solutions satisfy precise needs) of the solutions.
(Runco and Jaeger, 2012)	Design related	The standard definition is bipartite: Creativity requires both originality and effectiveness.
(Lopez-Mesa and Vidal, 2006)	Design related	Creativity is generally regarded as the ability to develop novel and useful ideas.
(Grace et al., 2015, p.125)	Design related	"…creativity as union of novelty, value, and surprise".
(Howard et al., 2006)	Design related	A novel idea that is both unobvious and appropriate.
(Kelly and Gero, 2017, p.149)	Design related	"…criteria of being both useful and novel…surprising as a third criteria."

Table 2.2. Representative definitions of creativity relating different domains

Efforts to define creativity had shifted towards exploring and defining highly eminent creativity (big-C creativity) and ordinary creativity (little-c creativity) separately since the 1980s (Chan, 2015, Craft, 2000). Similar distinctions of creativity include "exceptional" or "mundane" creativity (Barsalou and Prinz, 1997), as well as being historical creative (h-creative) or psychological creative (p-creative) (Boden, 2003). Researchers started to realise the complexity of creativity and the possible factors that may affect creativity, including cognitive ability, learning style, knowledge, motivation, personality and environment (Amabile, 1983a). A selection of representative definitions for big-C creativity and little-c creativity are described in Table 2.3.

Definitions for Big-C creativity	
(Feldman et al., 1994)	The achievement of something remarkable and new, something which transforms and changes a field of endeavour in a significant way… things people do that change the world.
(Vernon, 1989)	A person's capacity to produce new or original ideas, insights, restructurings, inventions or artistic objects, which are accepted by experts as being of scientific, aesthetic, social, or technological value.
(Ryhammar and Brolin, 1999)	Exceptional human capacity for thought and creation.
(Dacey et al., 1998)	The ability to produce new knowledge.
(Barsalou and Prinz, 1997)	Whereas exceptional creativity graces a few individuals
(Csikszentmihalyi, 1999)	The creative outcomes of those highly competent in their given domain.
(Boden, 2003, p.43)	"Both are initially defined with respect to ideas, either concepts of styles of thinking…The historical sense applies to ideas that are fundamentally novel with respect to the whole of human history."
Definitions for little-c creativity	
(Craft, 2000)	The kind of creativity which guides choices and route-finding in everyday life, or what I have come to term 'little c creativity'; Creativity involves being imaginative, going beyond the obvious, being aware of one's own unconventionality, being original in some way. It is not necessarily linked with a product-outcome.

(Seltzer and Bentley, 1999)	Creativity is the application of knowledge and skills in new ways to achieve a valued goal. To achieve this, learners must have four key qualities: 1. The ability to identify new problems, rather than depending on others to define them; 2. The ability to transfer knowledge gained in one context to another in order to solve a problem; 3. A belief in learning as an incremental process, in which repeated attempts will eventually lead to success; 4. The capacity to focus attention in the pursuit of a goal or set of goals.
(Barsalou and Prinz, 1997)	Mundane creativity graces everyone
(Boden, 2003)	Both are initially defined with respect to ideas, either concepts of styles of thinking…The psychological sense concerns ideas that are fundamentally novel with respect to the individual mind which had the idea

Table 2.3. Representative definitions for big-C creativity and little-c creativity

The distinction between definitions of big-C creativity and small-c creativity is worth reviewing because the research aim for this study is to develop an analogy-empowered creative design process which can be adopted for design of enterprise. The process, as a support derived from the study, is for the improvement of generic models for enterprise development, thus enhancing ordinary everyday creativity. The expected outcome is highly specific and requires gradually convergent focus from the starting point of this study where the research realm of creativity is broad. After all, concentration is necessary when "approaches to and definitions of creativity remain highly divergent" (Kahl et al., 2009, p.1).

As research on creativity progresses, the thinking on definition of creativity will continue to evolve, which could lead to different criteria on the two elements of standard definition of creativity: originality and effectiveness (Runco and Jaeger, 2012). For instance, there could be a third element to creativity: surprise (Simonton, 2012, Simonton, 2018). This study is concerned about creativity in design, as it focuses on the use of analogical thinking to enhance creative output in design. A further review of definition of creativity in design domain is conducted, and the findings indicate that creativity in design is defined similarly and consistently with other domains. The difference in elements of definition for creativity is illustrated in Table 2.4 i.e. an element of novelty, elements of novelty and usefulness, and elements of novelty, usefulness and surprise.

Elements	Representative definition	Source
Novel (new, original, different)	"The act of creating something new, a new insight, a new theory or a novel design"(Eckert et al., 2012, p.338)	(Coyne, 1997); (D'souza and Dastmalchi, 2016); (Kazerounian and Foley, 2007); (Keshwani et al., 2017); (Oman et al., 2013)
Novel and Useful (valuable, appropriate, feasible, meaningful)	"The standard definition is bipartite: Creativity requires both originality and effectiveness"(Runco and Jaeger, 2012, p.92)	(Doboli and Umbarkar, 2014); (Jeffries, 2007); (Kim et al., 2007); (Lee et al., 2015); (Robertson et al., 2007); (Sarkar and Chakrabarti, 2011); (Sosa and Marle, 2013) (Tan, 2016); (Toh and Miller, 2015); (Valgeirsdottir et al., 2015); (Lopez-Mesa and Vidal, 2006)
Novel, Useful and Surprising (unexpected, unobvious)	"A novel idea that is both unobvious and appropriate"(Howard et al., 2006, p.550)	(Grace et al., 2015); (Kelly and Gero, 2017); (Hakak et al., 2016); (Snider et al., 2016)

Table 2.4. A selection of definitions for creativity in design by elements

The key essence of creativity is unchanged in the domain of design, with only adaptions made in the design context to assist deliver design output including products, processes and potentially enterprises. It can be therefore concluded that research on the definition and output of creativity will ever develop. For this study, a working definition of a creative idea is derived from above review and described as:

"An idea with novel, useful, and surprising elements."

2.1.2. Creative Problem Solving (CPS)

The design process can be viewed as a problem solving process, and involves creativity (Chan, 2015). An analogy-empowered creative design process is proposed in Chapter 7 and implemented in Chapter 8, and is thus worth reviewing the evolution of Creative Problem Solving (CPS). CPS has been systematically studied for over six decades and a sequencing system similar to software versions is introduced to mark the footpath of development (Treffinger, 2005b). Among the six major developed CPS models up to date, three tendencies of modifications can be highlighted. 1) a thinking style evolved from processes dominated by divergent thinking to a highly balanced combination of divergent thinking and convergent thinking. This significant change began with the modification from the Osborn-Parnes CPS model (version 2.2 cited by (Isaken))(Noller, 1976) to version 3.2, and CPS model version 5.0 (Isaksen, 1993) 2) increased flexibility by adopting a more descriptive and less prescriptive process. The difference between CPS version 4.0 (Treffinger, 1992) and 5.0 clearly demonstrates this development. 3) the style of CPS models changed from a mainly theoretical expression to a more experimental examination. This does not imply that real application of early versions is neglected. In fact, CPS version 2.0 was applied in a two-year experimental creativity studies project at Buffalo State College, and the results supported the model (Noller, 1972, Parnes, 1987). Through the generations of CPS models, experimental examination is more and more concerned with the feasibility of the model. Compared to the early models, the latest version (6.1) is more comprehensive and flexible.

a. Critical review of evolving CPS models

Since the first seven-step CPS model introduced as shown in Table 2.5 (Osborn, 1953), there have been five major developments and modifications associated with relevant models. In order to look for the research potential of CPS, it is essential to understand the evolvement of generations of CPS models. Osborn's first generation of CPS model marks the starting point of explicit research on this area and outlines a defined thinking route for CPS for the first time.

1	Orientation	Pointing out the problem
2	Preparation	Gathering pertinent data

3	Analysis	Breaking down the relevant material
4	Hypothesis	Piling up alternatives by way of ideas
5	Incubation	Lifting up to invite illumination
6	Synthesis	Putting the pieces together
7	Verification	Judging the resultant ideas

Table 2.5. Osborn's seven-step CPS model (Osborn, 1953)

Parnes and Nollers' work on CPS model development concentrated on the core fragment of problem solving, thus the five findings as shown in Figure 2.1. However, their CPS model is not adequately comprehensive due to the remaining linear thinking process and a lack of attention on convergent thinking.

Figure 2.1. Osborn-Parnes Five-Stage CPS model (Parnes, 1967a, Parnes, 1967b)

Realising this issue and need for improvement, Isaksen and Treffinger introduced an equal amount of convergent thinking and divergent thinking in a parallel manner in their modified CPS model which is illustrated in Figure 2.2. Fact-finding is also replaced by Data-finding, as individual subjective opinions of problem solvers are suggested to also have affected the thinking process, so pure facts are not sufficient (Isaksen, 1985). It is also suggested that an extra Mess-finding component should be added at the front end of the CPS model, covering background information like thinkers' experiences and task aims. The Mess-finding step seems unnecessary in the sense that, when a team face a problem-solving situation, the factors and background of ownership are hardly variable, thus concentration should be placed on the Data-finding of the problem itself.

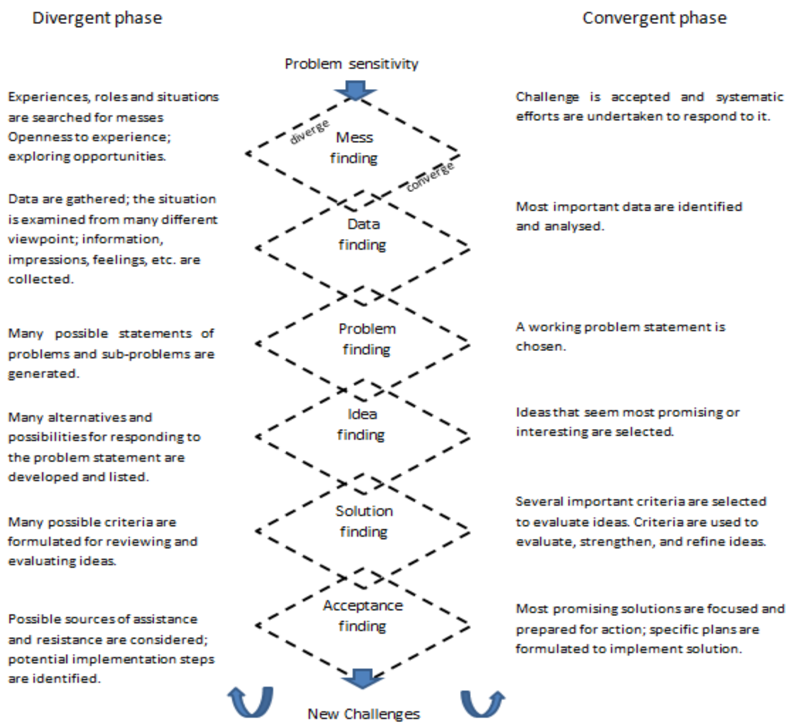


Figure 2.2. CPS process model featuring convergent thinking (Isaksen, 1985)

For the fourth generation of CPS model (Treffinger, 1992), all six steps are regrouped into three major stages in order to address the importance of the model's flexibility in application. Problems in reality can be complex and full of variables, thus a CPS model with restrictions is less applicable. This seemingly straightforward alternation might first have appeared insignificant; however, it was later proven by more than 40 research projects' findings that increased flexibility does indeed contribute to problem-solving using the CPS model (Treffinger, 2005a).

The subsequent CPS models become more descriptive and less prescriptive, which effectively increases flexibility when applying CPS to complex problems. These models for the first time abandon a sequential style, and thus prevent the problem solvers from restrictions with prescriptive steps. In fact, they are free to only adopt several of them in various orders and repeat when necessary, as illustrated in Figure 2.3. The other main new development of the latest model is that problem-solvers are allowed to evaluate whether CPS is suitable before planning actual actions through the process. A selection of mainstream CPS models and models with adjustments are presented in

Table 2.6 in chronological order for a more comprehensive understanding of the evolution of CPS.

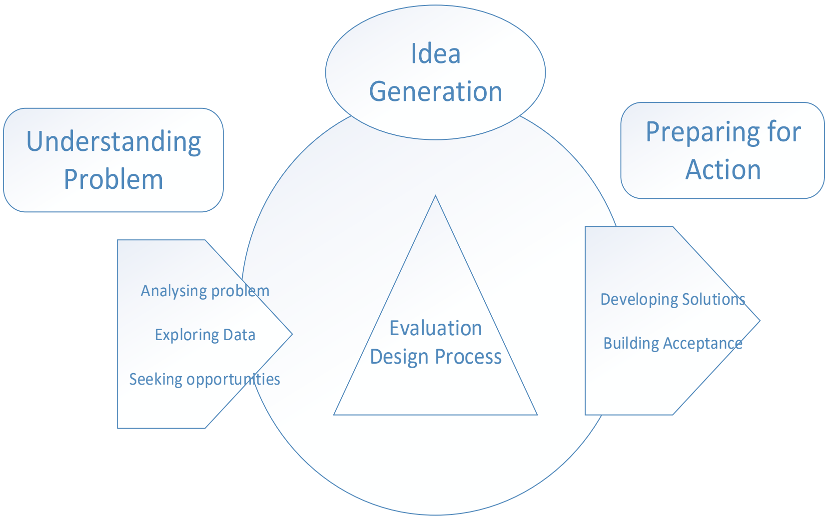


Figure 2.3. Descriptive CPS model (Isaksen, 2000b)

b. Human elements and potential development for CPS

Naturally, the output of CPS research is to apply it for real tasks. In practice, human behaviours are a key consideration in the application of CPS. It is essential for human beings involved in CPS to balance their creative thinking (divergent thinking) and critical thinking (convergent thinking) to achieve enhanced creativity (Cortes et al., 2019). People play different roles through the problem-solving process. Based on the different degrees of influence people have, there are three different roles in CPS. A client is a person who makes decisions and provides background information to a given problem, and a facilitator organises the problem-solving process while a resource group contributes by generating ideas. In order to solve a problem, a group is required to work together seamlessly. The importance of human elements is also highlighted in the research of the design process (d.school, 2010) (see Section 7.2.2), and is preserved as an essential element in the proposed creative design process in Chapter 7.

The four-stage model for group development indicates a typical tendency of group development, thus variations should occur in practice, where characters of task and styles of group vary (Jones, 1983). The importance of human elements in the problem-solving process inspires the thinking on human-centred element of empathy, which is embedded in the proposed creative design process in Chapter 7.

As an essentially creative process, CPS acts as an effective model to contribute to the thinking process of problem solving. A brief review of creative processes suggest that theoretical analysis and development of creative processes have generated a fruitful outcome, as illustrated in Table 2.6. The commonality in thinking and structure of these creative processes can be easily identified. The integration of a creative process into a practical design process could enhance the creative output and therefore benefit design. Furthermore, a creative design process featuring more specific creativity elements could potentially provide extra effectiveness and surprising factors in the outcome of design activities. Such potential leads to the application of creative process in an engineering design project in Chapter 6. An analogy-empowered integrated creative design process for enterprise is described in Chapter 7 and is further applied in Chapter 8.

Model by author	Analysis phase			Generation phase	Evaluation phase	Communication / implementation phase	
(Dewey, 1910)	Felt difficulty and location and definition			Suggestion of possible solutions	Development by reasoning of the bearings of the suggestion	Further observation and experiment resulting acceptance/ejection	
(Wallas, 1926)	(possible overlapping in all stages) Preparation			Incubation & Illumination	Verification	X	
(Kris, 1952)	X			Inspiration	Elaboration	Communication	
(Osborn, 1953)	Orientation, preparation and analysis			Hypothesis & incubation	Synthesis & verification	X	
(Guilford, 1956)	X			Divergence	Convergence	X	
(Osborn, 1963)	Fact-finding			Idea-finding	Solution-finding	X	
(Parnes, 1967a)	Problem, challenge, opportunity	Fact-finding	Problem-finding	Idea-finding	Solution-finding	Acceptance-finding	Action
(Jones, 1970)	Divergent: Search data & map problem			Transformation: Pattern-making, flashes of insight, changes of set	Convergent: Make decision	X	
(Svensson, 1974)	Definition of the problem	Gathering relevant information	Period of incubation	Generation of ideas	Verification & modification	X	

<table>
<tr><td>(Parnes, 1981)</td><td colspan="2">Mess finding</td><td colspan="2">Problem-finding</td><td>Idea-finding</td><td>Solution-finding</td><td colspan="3">Acceptance-finding</td></tr>
<tr><td>(Isaksen et al., 1994)</td><td>Constructing opportunities</td><td colspan="2">Exploring data</td><td>Framing problem</td><td>Generating ideas</td><td>Developing solutions</td><td>Building acceptance</td><td>Appraising tasks</td><td>Designing process</td></tr>
<tr><td>(Amabile, 1996)</td><td colspan="2">Problem or task presentation</td><td colspan="2">Preparation</td><td>Response generation</td><td>Response validation</td><td colspan="3">Outcome</td></tr>
<tr><td rowspan="2">(Basadur et al., 2000)</td><td>Problem finding</td><td colspan="2">Fact finding</td><td>Problem definition</td><td>Idea finding</td><td>Evaluate and select</td><td>Plan</td><td>Acceptance</td><td>Action</td></tr>
<tr><td colspan="9">Active divergence and Active convergence</td></tr>
<tr><td>(Lubart, 2000)</td><td colspan="4">Preparation</td><td>Incubation (creative frustration) & Illumination</td><td>Verification</td><td colspan="3">X</td></tr>
<tr><td>(Runco and Kim, 2011)</td><td colspan="4">Preparation</td><td>Incubation & Inspiration</td><td>Verification</td><td colspan="3">X</td></tr>
<tr><td>(Tidwell et al., 2019)</td><td colspan="2">Assessing existing knowledge</td><td colspan="2">Building knowledge to fill gaps identified</td><td>Creating</td><td colspan="4">Delivering & evaluating the intervention</td></tr>
</table>

Table 2.6. A selection of creative processes

2.2. Review of Creativity Tools

Creativity tools aim to enhance creativity; they are designed to help the users follow a more effective pattern towards creativity, following which creative solutions are more likely to emerge. The Investment Theory in cognitive psychology suggests that creativity requires six categories of resources: intellectual capability, knowledge and experience, cognitive ability, motivation, personality and environment (Sternberg, 2006, Amabile, 1983a). The effective use of creativity tools aims to lead to enhanced creativity in given resources and restrictions. Several core creativity tools including brainstorming, morphological analysis and checklist, which are mostly relevant to engineers (Lordan and Thompson, 1999). Higgins listed 101 creativity tools and included the evaluation attributes of application, such as time, quantity and novelty of ideas, ease of use etc. (Higgins, 1995). 97 creativity tools have been analysed and categorised into seven groups: 1) Conditioning/motivating/organizing techniques; 2) Randomisation; 3) Focusing techniques; 4) Systems; 5) Pointed techniques; 6) Evolutionary directed techniques; and 7) Innovation Knowledge-based techniques (Zusman, 1999). 192 creativity tools are listed and introduced by a UK-based company in alphabetical order, under the five categories of problem definition, idea generation, idea selection, idea implementation and processes (mycoted, 2015). Yan has analysed 60 creativity tools with a novel approach to including relations with personality traits and personality types (Yan, 2017).

Based on an understanding of creativity tools in theory and application, this study benefits from such understanding and focuses on new applications and connections as research outputs (see the research questions in Chapter 5). The review or use of a selection of tools can be identified in this thesis, including Brainstorming/Brainwriting, Creative Problem Solving, Morphological Analysis, TRIZ, Synectics, SWOT analysis, Six Thinking Hats, SCAMMPPER, Analogical Thinking and CATWOE.

2.3. More detailed review of typical Creativity Tools

2.3.1. Brainstorming (Brainwriting)

a. Overview

Brainstorming (Brainwriting) has been conducted as an ideation tool in all the case studies mentioned in this study (see Chapter 6). It is originally introduced as an effective component of the CPS process, in order to supplement individual ideation (Osborn, 1953) and is by far one of the most well-known and widely-studied idea generation tools. Brainstorming is reviewed in detail here as it involves divergent and convergent thinking, and is an important tool for ideation. Brainstorming is likely to be more powerful and effective at idea generation when the proper procedure is followed and conducted by experienced facilitator, who would provide facilitation with corrective feedback(Paulus, 2019). Some studies on brainstorming reported in conclusion that brainstorming performs less efficiently than individual ideation because the experiments are inappropriately structured and fail to seize the essential core of Osborn's recommendations (Diehl, 1991, Nickerson, 1999). The famous reputation of the term brainstorming is akin to a double-edged sword, as it contributes to the wide applications of this tool as well as encouraging its unconscious misuse. Nowadays, it is not abnormal that people refer to a group discussion or even a casual chat as brainstorming, scenes of which appear frequently in TV programmes such as the BBC's Apprentice. It is necessary to investigate the brainstorming process in detail if we are to understand its advantages and prevent possible misconduct.

Comprehensive recommendations on how brainstorming should be conducted and by what procedure, as illustrated in Figure 2.4, are made originally by Osborn (Osborn, 1953) and supported later by many other researchers (Isaksen, 2000a).

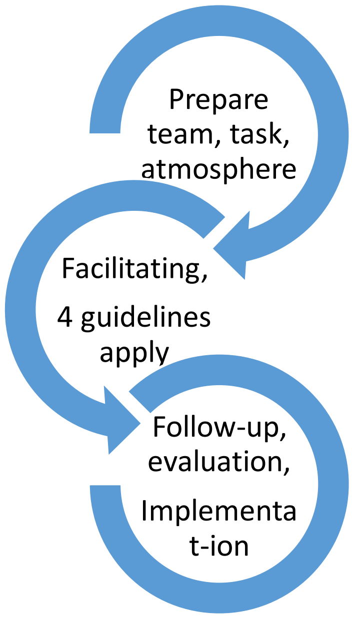


Figure 2.4. Recommended procedure of brainstorming (Osborn, 1953)

b. Critical review of factors within Brainstorming

A well-organised brainstorming session can lead to the generation of a large amount of ideas, which will contribute to problem solving. However, many researchers have pointed out that due to either underestimation of the core guidelines or misconduct of them, barriers to idea generation using brainstorming do exist. Especially in the early stage of a brainstorming session, when the participants are not warmed-up and the dynamic and equal atmosphere has not yet been established, the likelihood of certain participants dominating the discussion is high. The reason for there being less involvement of the other members is considered to be fear of judgement and evaluation to their potential ideas (Dunnette, 1963, Maginn, 1980). From the author's perspective, this phenomenon is to some extent inevitable because of the weakness of human nature, but is definitely improvable by introducing well-designed system which the facilitators adopt to avoid partly uneven involvement.

Contrary to the guideline of 'freewheeling is welcomed', cognitive inertia may take effect and lead to linear extension of certain ideas, rather than the production of 'off the wall' ideas as is initially desired (Bouchard, 1974). Another barrier against successful brainstorming is social loafing, which has been discussed in numerous studies (Karau, 1993, Shepperd, 1993). Although social loafing exists at almost every aspect of teamwork, brainstorming apparently has less tolerance as its opposing effect to the essence of brainstorming. One reason for social loafing is considered to be loss of personal accountability within the context of group or team, as unlike individually, in a group one specific member is less likely to be held either accountable for team achievement or responsible for team failure (Kerr, 1983). Thus, an individual member can have a tendency to avoid an exceptionally high performance within a team as there is nothing for the team member to gain for that, while the member does not mind the performance sliding into the lower spectrum for nothing to lose.

A magnification of team context will result in a significant reduction of efficiency and productivity. In order to tackle the social loafing from this aspect, both a majority-recognized reasonable evaluation system and a proportionately rewarding system are necessary. The evaluation system distinguishes team members' effort and the rewarding system encourages higher performance. A punishing system associated with the rewarding system is unnecessary, not only because it would be redundant, but also because it is likely to cause negative effect within the team and thus offset the advantages of the application of both systems. Another possible cause for social loafing is considered to be the reduced personal influence of an individual when the number of team members increases (Ruback, 1984). When an individual makes a decision, there would be no opposition, thus the individual has full influence on the decision. But if a decision needs to be made by a group of individuals, each would have limited impact on the decision and the degree of impact decreases alongside the increasing size of a team.

Another negative factor might occur during brainstorming is the "sucker effect", which significantly reduces the team efforts and results (Zalesny, 1990). When an individual member of a team starts to suspect that other members might not work as hard as himself/herself, to match the others' efforts, personal effort is likely to be deliberately reduced in order not to take on the heaviest burden within the team (Orbell, 1981).

One more challenge in practice for brainstorming is the technical bottleneck of its procedure: the production blocking. This means that the amount of ideas generated suffers from the fact that, at a given time, only one member is expressing ideas while the rest is unable to express their ideas (Bouchard, 1970). It is suggested by numerous researchers that tape-recording improves this limitation by achieving simultaneous processing during brainstorming. Moreover, participants are instructed to note down their ideas before offering them to the team (Osborn, 1953, Bouchard, 1972).

c. Importance of facilitators in Brainstorming

The importance of facilitators during brainstorming was originally concluded by Osborn (Osborn, 1953) and has been continuously re-examined in details by numerous studies (Offner, 1996, Oxley, 1996). The best type of research for this aim should be open-minded and exploring, without prejudice and expectations for either side of the subject. One of such experiments, exploring the use of facilitators as well as differences that beforehand instructions make, is conducted by comparing the performance of brainstorming groups (Isaksen, 2005). Although explicit numeral comparison can be obtained from the results table for this experiment, non-quantifiable analysis makes more sense as one particular experiment is to some extent random and discovering the tendency hiding behind data is more important.

An interesting development of this experiment is to demonstrate the effectiveness of brainwriting. In brainwriting, participants are requested to write their own ideas down on paper and then exchange them, with improvements of existed ideas being encouraged. The simultaneous processing and improving of ideas eliminate the productivity-blocking barrier of brainstorming (Geschka, 1975). This is one of the successful improvements on tackling barriers of brainstorming. Furthermore, the results show a brainwriting group works more effectively with a facilitator who also generates ideas.

This research answers some strong arguments against brainstorming which point out that brainstorming is a myth and works less efficiently than individuals (Furnham, 2000). Although both sides have reasonable arguments and evidence, the disadvantages of brainstorming have been those that Osborn emphasised. From this viewpoint, any new contributions on eliminating these disadvantages are welcomed and will benefit the research and application of this creativity tool.

To summarise the most effective manners of applying brainstorming, it is essential to understand the essence of it and also have confidence in its performance. When it comes to the effect of brainstorming on idea generation, either overestimation or underestimation is inappropriate. Brainstorming as a tool for group ideation should only be adopted as supplement for individual idea generation, but not as a substitute. The application of brainstorming would benefit from research on improving the effectiveness by introducing smart techniques to tackle the caveats.

2.3.2. Review of TRIZ

TRIZ, translated from a Russian acronym, stands for "Theory of Inventive Problem Solving" and was originally developed by G. S. Altshuller after analyses of patterns of inventions (Lordan and Thompson, 1999). Through the review of hundreds of thousands of inventions, the characteristics of inventive solutions have been generalised into patterns which form the theory of TRIZ. It has been observed that the existence of technical problems and their innovative solutions has a repeatable pattern, and exploration within a selection of inventive principles can lead to suitable solutions. TRIZ is a highly structured tool and requires pre-knowledge and practice to maximise its power. A typical operation process with TRIZ is as follows:

a. To analyse the problem and identify the critical features using 39 suggested parameters.
b. To discover the contradictions within the contradiction matrix between each pair of the 39 parameters in every cell.
c. To locate inventive principles within the contradiction matrix as a reference for solutions.
d. To analyse the suggested inventive principles listed in Table 2.7 for potential solutions to the problem.

1. Segmentation	11.Cushion beforehand	21.Skipping	31.Use of porous materials
2. Extraction	12. Equipotentiality	22.Convert harm into benefit	32.Colour changes
3. Local quality	13. Inversion	23.Feedback	33. Homogeneity
4. Asymmetry	14. Spheroidality	24.Mediator	34. Rejecting and regenerating parts

5. Combination	15. Dynamics	25.Self-service	35. Transforming physical or chemical states
6. Universality	16.Partial or excessive actions	26.Copying	36. Phase transitions
7. Nesting	17.A new dimension	27.Inexpensive short life	37.Thermal expansion
8. Counterweight	18.Mechanical vibration	28.Substitution of a mechanical system	38. Strong oxidisers
9. Prior counter-action	19.Periodic action	29.Pneumatic or hydraulic systems	39. Invert environment
10.Prior action	20.Continuity of useful action	30.Flexible film or thin membranes	40. Composite materials

Table 2.7. 40 Inventive Principles in TRIZ (Gadd, 2011)

TRIZ can be used in both individual and group creative ideation, while relevant trainings are necessary. It provides a toolbox for inventive solutions to not only engineering problems, but also to more universal problem-solving in product design, management and business to break psychological fixation (Adams et al., 2009). An adapted TRIZ contradiction matrix in Chinese is shown in Appendix 1, which was utilised in an example of TRIZ application to tackle technical problems in aircraft design.

2.3.3. Review of Morphological Analysis

Morphological Analysis (MA) was introduced by Zwicky as a tool to systematically analyse the technologies of a jet engine. The source word "morphology" refers to "the form and structure of anything" according to Collins Online English Dictionary (https://www.collinsdictionary.com/dictionary/english/morphology). MA analyses a complex system and breaks the challenge down into sub-systems of parameters or dimensions, and then for each sub-system all the possible solutions are listed. Therefore, theoretically the combinations of values from each dimension will cover all possible over solutions to the targeted research problem (Zwicky, 1969). A typical MA matrix is shown in Table 2.8.

MA analysis	Parameter A	Parameter B	Parameter C	D, E, F…
Solution a	a to A	a to B	a to C	……
Solution b	b to A	b to B	b to C	……
Solution c	c to A	c to B	c to C	……
d, e, f…	……	……	……	……

Table 2.8. Structure of a typical MA matrix

The structure of a typical MA process that the author would follow is as follows:

a. To analyse the problem and identify all parameters as sub-systems.
b. To list and analyse all identified parameters.
c. To form a multi-dimensional matrix by filling up all possible solutions as values to each and every parameter.
d. To assess the feasibility of solutions within the matrix by cross-consistency check, which helps reduce the solution space.
e. To evaluate all feasible solution combinations and select the most suitable solutions.

Evidently, MA is a powerful tool to systematically search for best solutions to a complex problem, as it in theory offers all possible combinations to the solution space. It is a tool suitable for both individual and group use (Ritchey, 2011). MA as a creativity tool is applicable to fields such as product/service development, market research, technology innovation and policy making (Ritchey, 2011). For instance, morphological analysis helps the exploration of design space for input devices for human-computer interaction (Card et al., 1991). MA assists in filling up the gaps of solutions, exploring the maximum of solution space and keeping records of such exploration. However, in practice the workload from phases such as cross-consistency check, feasibility check and evaluation of solutions could be unacceptably high. This is due to the inherent nature of MA applying matrix calculation. Recent developments to tackle such challenges include introducing computational software to reduce the workload of consistency check and evaluation, while improve the accuracy and user experience in MA (Ritchey, 2011, Garvey, 2016, Ritchey, 2009).

2.3.4. Review of Synectics

Synectics is an analogy-based creativity tool effective for group use to abstract new information, generate writings and general problem-solving. Synectics is derived from the Greek word *synectikos*, meaning "to bring different things into unified connection" (Svensson, 1974). It endeavours to take advantage of the huge capability of minds to connect seemingly irrelevant elements of thinking, to form new understandings, new ideas, and new solutions to problems. Analogy and analogical mapping are the source of Synectics' power, as it relies on the capability of thinkers to establish analogical mappings through the application to stimulate new insights. The essence of Synectics is to make strange into familiar and to make familiar into strange (Gordon, 1961). Being able to think outside the box with the assistance of analogy, new solutions to problems are made possible. A facilitated ideation process using Synectics could include the steps listed below (Lordan and Thompson, 1999):

a. To analyse the given problem and try to make the strange familiar by understanding the problem.
b. To try to eliminate instant or conventional response as solutions to the problem, but to provide further information during the elimination process.
c. Thinkers are encouraged to express their understanding of the problem by use of fantasy analogy, and to provide a selection of viewpoints of the problem.
d. The facilitator decides a viewpoint for the thinkers to concentrate on, and with the application of direct analogy, personal analogy, symbolic analogy and fantasy analogy the thinkers could examine the problem further by making familiar strange. A selection of analogies will be chosen for further analyses and elaboration.
e. The developed analogies are to be applied to the problem situation for potential solutions. Further iterations could be carried out with requirements for the search for suitable solutions.

Following the suggested steps above, Synectics helps to break psychological fixation of mindsets towards an understanding of a problem and encourages the use of analogies to stimulate innovative solutions. Synectics provides additional advantages of heuristic thinking on top of traditional analytical thinking to enhance idea generation for design (Koziolek, 2017). During the process of making familiar strange, analogy is adopted, not in a structured fashion on reasoning, i.e. systematic analyses of attributes and relations to establish analogical reasoning, but in a more straightforward way of involving both logic and psychologic analogies (Roukes, 1988). However, Synectics has disadvantages in that the effective application of Synectics requires thinkers' capacity of analogical thinking and experienced facilitation. In addition, the thinking process can be time-consuming and demanding (Adams et al., 2009). Synectics is a structured creativity tool embedded with the power of analogy, and its effective application could lead to innovative and outstanding ideas being generated.

2.3.5. Review of SWOT Analysis

SWOT analysis is formed by analyses on Strength, Weakness, Opportunities and Threats. It is categorised as a class A creativity tool for the Internal Mapping phase, because its effectiveness output is high when considered the ease of use, no requirements for training, and versatility for a range of application areas such as product or service development, business strategy and market research (Boone and Kurtz, 1992, Jackson et al., 2003). SWOT provides clear and targeted directions for ideation, which would compel the thinkers to generate structured ideas with guidance. SWOT analysis can be used as an individual ideation tool, but is often found as a group creativity tool with the aid of a questionnaire. Apparently, different criteria require different sets of questionnaires. A typical questionnaire could include the questions shown in Table 2.9.

SWOT analysis	**Example Questions**
Strengths	What are our advantages? What strategic resources do we have?
Weaknesses	What aspects can we improve to enhance the performance? What should we do differently for better outcomes?
Opportunities	What are the most powerful trends that we know? Where to find the opportunities for future development?
Threats	What are the competitors' stances in the current market?

	What are the technical challenges we may face?

Table 2.9. A set of example questions for SWOT analysis

SWOT analysis does not have to be applied in a linear manner, but as a more sophisticated matrix e.g. TOWS Matrix (Weihrich, 1982). A TOWS Matric is based on the distinguished external and internal parameters involved. Threats and Opportunities are external parameters while Weaknesses and Strengths are internal parameters. A representative TOWS Matrix is illustrated in Table 2.10, which is adopted as an effective planning tool for university strategies (Dyson, 2004). The analyses of combination of paired parameters would reveal a more in-depth understanding compared to the analyses of single parameters.

	Strengths	**Weaknesses**
Opportunities	SO analysis	WO analysis
Threats	ST analysis	WT analysis

Table 2.10. The TOWS Matrix

SWOT analysis is more structured with guidance compared to brainstorming, due to its explicit direction for analysis. It also benefits from the wide acceptance of usage across companies and industries (Dyson, 2004). As a straightforward creativity tool without pre-training requirements, it is effective and helpful as a starting point to understand the current situation for development of product/service as well as business.

2.3.6. Review of Six Thinking Hats

Six Thinking Hats enables thinkers to view a given problem from a series of different viewpoints, which helps thinkers focus on a specific aspect of problem at any single time to reduce distraction. The tool was developed by Edward Debono in his book Six Thinking Hats and has been useful in assisting decision making and collective problem solving (Bono, 1999). The tool can be adopted by a group of thinkers with a facilitator, who can also participate in the ideation process. Adaption for individual use is also feasible. The specific thinking angles represented by the colours are explained in Table 2.11.

Colour	Representation	Explanation
White hat	Facts	To identify the factual data available and the knowledge gaps to either fulfil or to acknowledge
Red hat	Emotions	To express emotional views of the decision
Black hat	Cautions	To investigate the drawbacks and weaknesses cautiously and defensively
Yellow hat	Positiveness	To take the optimistic viewpoint to help realise benefits and values of decision
Green hat	Creativity	To think creatively for alternative solutions
Blue hat	Hat of order	To control the wearing of hats and discipline

Table 2.11. Detailed information on Six Hat Thinking

It is envisaged that objective thinking (White hat), subjective thinking (Red hat), Critical thinking (Black hat), Constructive thinking (Yellow hat) and Creative thinking (Green hat) cover the main modes of thinking, with Blue hat used as control and facilitation to the thinking process. Six Thinking Hats regulates thinking angels by a series of important perspectives, and switches between such perspectives to achieve lateral thinking. The blue hat decides the thinking order and has the power to discipline any disruption. Its ease of use and fun elements in application also help contribute to effective decision making and problem solving. Six Thinking Hats permits the thinker to focus on one mode of thinking at a time to reduce confusion, helps reduce any ego-involvement of the thinker by the symbolic use of hats, and promotes an exploratory thinking style. All these three elements make Six Thinking Hats a valuable thinking tool (Carl, 1996).

Six Thinking Hats can be applied as a creativity tool for both idea generation and evaluation, but the broad-minded style may not be suitable for all participating thinkers (Adams et al., 2009). In practice, the facilitator’s experience would make a significant difference towards the outcome, therefore it would be important to ensure the quality facilitation of a Six Thinking Hats creative session.

Further examples of application of Brainstorming (Brainwriting) and other creativity tools such as SCAMPER and TRIZ(SLP) are demonstrated in case studies described in Chapters 6 and 8.

2.4. Conclusions

The research on creativity and creativity tools have generated many fruitful achievements and effective solutions from idea generation to decision making in areas, including engineering design. Among the hundreds of existing creativity tools where the algorithms of thinking are reflected, e.g. parallel thinking, divergent and convergent thinking. However, despite the effectiveness of these tools in application, limitations exist including a lack of systematic approaches, requirements for intensive training and facilitation, and a lack of intrinsic attributes. The effectiveness of a selection of creative tools has been reviewed in this and the following chapters. By analysing the algorithms behind the creativity tools, the source of the effectiveness can be reached, and thus potential improvements are possible.

Through a review of creativity, creative process and creativity tools, insights are obtained not only on the application process of creativity tools, but also on the reasons for the functioning of creativity tools. It is such insights that shed light on the future research on creativity and creativity tools. Analogy has been found in several creativity tools including TRIZ, Synectics, and Biomimetics. It would be meaningful to learn more about analogy and analogical thinking because analogy must have value to be able to form the core for these above-mentioned creativity tools.

The insights obtained through the literature review of creativity and creativity tools help to understand the fundamentals of creativity, and indicate any knowledge gap in creativity research. As a result, analogical thinking has been highlighted as a creativity tool with further potential for enhanced utilisation. Further study on analogy could potentially lead to either development of its application in creativity or more practical value in real-world design projects, or both.

Chapter 3. Review of Analogy in Creativity and Design

This Chapter reports the strategic review of analogy in existing literature to present key knowledge of analogy relevant to cognition and design, and to help clarify the research focus for this study. Both dictionary and academic definitions of analogy are searched to obtain understanding of the term, followed by the main theories of establishment of analogy. Relating to the study context, analogy in cognitive process and design is also investigated, in addition to analogy in selected creativity tools. The scope of review leads to key research focus and a proposed Analogical Creative Process for further investigation and application in the subsequent chapters. The review strategy is the same as in Chapter 2 (see Section 2.1).

3.1. Definitions of analogy

3.1.1. Definitions of analogy in major dictionaries and encyclopaedias

Analogy, or analogical thinking (reasoning) as a thinking style, has been considered as a central part of human creativity and cognition (Holyoak, 2001, Gentner, 1983, Hofstadter, 2001, Gentner, 2012). In order to understand the meaning of the word analogy, it is worth exploring its definitions in dictionaries and encyclopaedias as authoritative references. The various definitions of analogy from these sources are illustrated in Table 3.1.

Definition	Source	Reference
1. *"Agreement or similarity, esp. in a certain limited number of features or details"* 2. *"A comparison made to show such a similarity"* 3. *"(biology) the relationship between analogous organs or parts"* 4. *"(logic, mathematics) a form of reasoning in which a similarity between two or more things is inferred from an unknown similarity between them in other respects"*	Collins Dictionary	http://www.collinsdictionary.com/dictionary/english/analogy?showCookiePolicy=true last accessed on 24/07/2019

5. *"(linguistics) limitation of existing models of regular patterns in the formation of words, inflections, etc"*		
"A comparison between things that have similar features, often used to help explain a principle or idea"	Cambridge Dictionaries	http://dictionary.cambridge.org/dictionary/british/analogy last accessed on 24/07/2019
1. *"A comparison between one thing and another, typically for the purpose of explanation or clarification"* 1.1 *"A correspondence or partial similarity"* 1.2 *"A thing which is comparable to something else in significant respects"* 1.3 *"(logic) A process of arguing from similarity in known respects to similarity in other respects"* 1.4 *"(Linguistics) A process by which new words and inflections are created on the basis of regularities in the form of existing ones"* 1.5 *"(Biology) The resemblance of function between organs that have a different evolutionary origin"*	Oxford Dictionaries	http://www.oxforddictionaries.com/definition/english/analogy last accessed on 24/07/2019
1. *A) "a comparison of two otherwise unlike thinks based on resemblance of a particular aspect"* *B) "resemblance in some particulars between things otherwise unlike"* 2. *"Inference that if two or more things agree with one another in some respects they will probably agree in others"*	Merriam-Webster	http://www.merriam-webster.com/dictionary/analogy last accessed on 24/07/2019

3. *"correspondence between the member of pairs or sets of linguistic forms that serves as a basis for the creation of another form"* 4. *"correspondence in function between anatomical parts of different structure and origin"*		
1. *"Correspondence of quantities, proportion; (Mathematics) agreement of ratios. Obs."* 2. *"Correlation, harmony, agreement; correspondence or adaptation of one thing to another. Obs."* 3. *"a) A figure of speech involving a comparison; a simile, a metaphor. Obs.* *b) A comparison made between one thing and another for the purpose of explanation or clarification."* *4. "a) Similarity, resemblance; an instance of this. Now rare.* *b) Correspondence between two things, or in the relationship between two things and their respective attributes; parallelism, equivalence, or an instance of this. Chiefly with between, to, with."* *5." A thing which (or occas. person who) corresponds to or resembles another; a parallel, an equivalent, an analogue."* *6. "(Linguistics) a. Conformity of words or language to a regular or consistent pattern; (hence) a set of rules describing the behaviour of language or intended to govern its use.* *b. The use of apparent linguistic parallels as a basis for the creation or remodelling of words, inflections, or constructions; spec. (more fully false analogy) a process in which linguistic forms arise or are adapted on the*	Oxford English Dictionary	http://www.oed.com/view/Entry/7030?redirectedFrom=analogy& last accessed on 24/07/2019

basis of regularities in the forms of parallel examples already in existence, omitting the formative steps through which these models originally arose." *7. "a) Chiefly philos. Correspondence or resemblance between things, as a basis for reasoning or argumentation; (also occas.) an instance of this.* *b) Chiefly logic. The process of arguing form similarity in known respects to similarity in other respects; the use of parallel cases as a basis for reasoning; an instance of this."* *8. "Zoology and Botany. Resemblance of form or function between parts or characteristics in different organisms, spec. where these are of different evolutionary origin; an instance of this."*		
"Something that seems similar between two situations, processes etc."	Longman Dictionary of Contemporary English	http://www.ldoceonline.com/dictionary/analogy last accessed on 24/07/2019
1. *"A relationship of resemblance or equivalence between two situations, people, or objects, especially when used as a basis for explanation or extrapolation."* 2. *"(Geometry) The proportion of the equality or ratios."* 3. *"(Grammar) The correspondence of a word or phrase with the genius of a language, as learned from the manner in which its words and phrases are*	Wiktionary	http://en.wiktionary.org/wiki/analogy last accessed on 24/07/2019

ordinarily formed; similarity of derivative or inflectional processes."		
"An analogy is a relation of similarity between two or more things, so that an inference (reasoning from premise to conclusion) is drawn on the basis of that similarity. *An analogy is either the cognitive process of transferring information from a particular subject (the analogue or source) to another particular subject (the target), or a linguistic expression corresponding to such a process. "*	New World Encyclopaedia	http://www.newworldencyclopedia.org/entry/Analogyhttp://www.newworldencyclopedia.org/entry/Analogy last accessed on 20/05/2018

Table 3.1. Definitions of analogy in major dictionaries and encyclopaedias

Analogy has been referred to in subjects or disciplines including logic, linguistics, biology, philosophy, psychology, literature and cognitive science (Hofstadter, 2001, Holyoak, 2001, Vincent et al., 2006, Vincent and Mann, 2002, Ward, 2011, Ward, 1998, Gentner, 1989). In addition to the disciplines which appeared in the dictionary entries, research on analogy can also be found in subjects of arts, aesthetics, law, ethics, religion, child development and mathematics (Guarini, 2009). This research on analogy has its relatively explicit aim, which is to help boost creativity and assist design by analogy, thus the theories and models of analogy will concentrate on its research in cognitive science. The most ambitious argument for the value of analogy could be that analogy forms a critical part of core of human cognition (Hofstadter, 2001, Holyoak, 2001), although not the sole basis of cognition (Keane, 2001). The key cause for analogy playing such a fundamental role in cognitive science is that it provides an effective bridge linking the known to the unknown, thus the acquiring of new knowledge.

3.1.2. Definitions of analogy in academic literature

Typical key words are widely shared in the definitions in Table 3.1, including similarity (similar), relationship, comparison (comparable), one (existing) and another (new). In fact, most of these key words appear in every article or book accessible so far, which feature analogy research. Among these works, analogy gains numerous definitions. It is widely agreed that analogy is a comparison between two objects, or systems of objects, that are thought to be similar (Bartha, 2013). Gentner's Structure-Mapping Theory (SMT) is helpful in understanding the nature of more complicated analogies and in clarifying specific examples. According to this theory, an analogy is a mapping of knowledge from one domain (the base) onto another (the target) (Gentner, 1983). Furthermore, for the Structure Mapping Engine, analogy is defined as the recognition that "one thing is like another" if there is a mapping from a conceptual structure describing the first one to another conceptual structure describing the second (Falkenhainer et al., 1989). However, in their critique of Structure Mapping Engine, Chalmers consider analogy to be an aspect of a more general cognitive function called high-level perception, by which an organism constructs a conceptual representation of a situation (Chalmers, 1991). Chalmers later continues to explore the process of analogy in more detail; when people make analogies, they are perceiving some aspects of the structures of two situations—the essences of those situations, in some sense—as identical, which involves taking the representations of two situations and finding appropriate correspondences between components of one representation with components of the other to produce the match-up that we call an analogy (Chalmers, 1991).

A representative selection of definitions of analogy in the context of academic research is illustrated in Table 3.2 to illustrate common perception of analogy. The source fields include psychology and cognitive science, general problem solving and design. The domain of design is the prioritised field of concern as this study focuses on the improvement of creative design through analogical thinking. The definitions seem consistent in the core essence of analogy, which is the analogical mapping of relations from the source to the target domain.

Source	Definition of analogy	Research field
(Vosniadou, 1989, p.413)	*"One mechanism which has been recognized by scientists, philosophers and psychologists alike as having the potential of bringing prior knowledge to bear on the acquisition of, somethings, radically new information is analogy". "…analogical reasoning involves the identification and transfer of structural information from a known system (the source) to a new and relatively unknown system (the target)."*	General problem solving
(Gust et al., 2008, p.8)	*"The purpose of analogies is to adapt knowledge available about the source conceptualization such that it can be applied to the target in a way that new analogies inferences can be drawn."*	Cognitive science
(Gentner, 2012)	*The ability to perceive and use relational similarity between two situations.*	General analogy
(Gentner, 2018)	*Analogy is a kind of similarity in which the same system of relations holds across different sets of elements.*	General analogy
(Hall, 1989, p.39)	*"Defined as a representational mapping from a known source domain into a novel target domain."*	Design
(Qian and Gero, 1996)	*Where variables from another existing but appropriate design are introduced into the current design.*	Design
(Casakin and Goldschmidt, 1999)	*A likeness of relations, as in A:B::C:D, or A is related to B like C is related to D.*	Design
(Dahl and Moreau, 2002, p.48)	*"Analogical thinking has been proposed as a basic mechanism underlying creative tasks, in which people transfer information from familiar, existing categories (i.e. base domains) and use it in the construction of their new idea (i.e. the target domain)."*	Design

(French, 2002, p.200)	*"Our ability to see a particular object or situation in one context as being 'the same as' another object or situation in another context is the essence of analogy-making."*	Design
(Kokinov and French, 2003, p.1)	*"Analogy-making is the process of finding or constructing a common relational structure in the descriptions of two situations or domains and making inferences by transferring knowledge from the familiar domain (the 'base' or 'source') to the unfamiliar domain (the 'target')."*	Design
(Ball et al., 2004, p.495)	*"Analogical reasoning entails the use of 'source' information from a previous problem-solving episode as a means to facilitate attempts at solving a current, 'target' problem."*	Design
(Casakin, 2004, p.2)	*"Thinking in terms of analogy involves the transfer of prior knowledge from a familiar situation (named the source), to a situation that should be elucidated (named the target)."*	Design
(Christensen and Schunn, 2007, p.29)	*"Analogy involves accessing and transferring elements from familiar categories in order to use it in the construction of a novel idea."*	Design
(Kalogerakis et al., 2010, p.418)	*"Analogy in problem solving consists of the transfer of knowledge from a base domain to a target domain as a function of correspondence between these two."*	Design
(Gentner and Forbus, 2011, p.266)	*"Analogy is one in which a familiar base (or source) domain is mapped to a less familiar (or more abstract) target domain, with the result that a new prediction or explanation is mapped from the base to the target."*	Design
(Linsey et al., 2012, p.134)	*"Analogy has traditionally been viewed as a comparison between two items in which their relational or casual structure match."*	Design
(Moreno et al., 2016b, p.185)	*"Analogy or analogical transfer appears to support designers in identifying and reaching distant domains that*	Design

	enable the exploration of innovative or disruptive solutions based on experience or external sources of inspiration and knowledge."	
(Han et al., 2017, p.13)	*"The main purpose of identifying an analogy relationship is to transfer the knowledge from a familiar domain to generate inference about un unknown domain, in order to understand the less familiar domain."*	Design
(Goucher-Lambert et al., 2019, p.2)	*"Analogical reasoning is generally defined as the process by which information from a source is applied to a target through the connection of relationships or representations between the two (source and target)."*	Design
(Kittur et al., 2019, p.1870)	*"The ability to find and apply deep structural patterns across domains."*	Design

Table 3.2. A selection of definitions of analogy in academic research

3.2. Theories of analogy in creativity

3.2.1. Structure Mapping Theory (SMT) (Gentner, 1983)

Among the existing theories and models of analogy, Gentner's Structure Mapping Theory (SMT) is investigated and the basis for building new developments in creativity. The SMT of analogy best suits the realm of creativity and design for two main reasons. 1) SMT complies with the most typical existing analogies and explains them. 2) The SMT can be conveniently transferred through a step-by-step application, which means a great deal for the application of analogy in real design tasks.

Gentner's SMT offers an explicit approach to explain analogy. Two mapping principles of SMT are that: 1) it is relations between objects rather than the attributes of objects that are mapped over from the base domain to the target domain; and 2) as determined by systematicity, higher-order relations prior to lower-order relations during mapping, and predicates describing interconnecting relationships is more mappable than isolated predicates (Gentner, 1983).

Rutherford's atom model forms a good example not only for analogy, but also for the utilisation of SMT to analyse an analogy (Gentner, 1983). A set of predicates describing relations in a base domain consists of attractive force, distance, revolving movement and mass difference; all these relations are between the sun and the planet in the base domain of the solar system. A corresponding set of predicates describing relations in the target domain consists of attractive force, distance, revolving movement and mass difference, while these relations are between nucleus and electron in the target domain of atom, as illustrated in Figure 3.1. The mathematic expressions of both systems are illustrated in the equations below.

$$F_{grav} = \frac{Gm_p m_s}{R^2}$$

$$F_{elec} = \frac{-q_e q_n}{R^2}$$

Newton's law of gravitation states that "any particle of matter in the universe attracts any other with a force varying directly as the product of the masses and inversely as the square of the distance between them". In the context of the solar system, F_{grav} is the gravitational force, G is the gravitational constant, m_p is the mass of the planet, m_s is the mass of the sun, and R is the distance between the centres of the planet and the sun.

Coulomb's law describes that 'the magnitude of the electric force *F* is directly proportional to the amount of one electric charge, q_1, multiplied by the other, q_2, and inversely proportional to the square of the distance *r* between their centres.' In the case of Rutherford's atom model, F_{elec} is the magnitude of the electric force, q_e is the electric charge of electron, q_n is the electric charge of nucleus, and R is the distance between the centres of nucleus and electron.

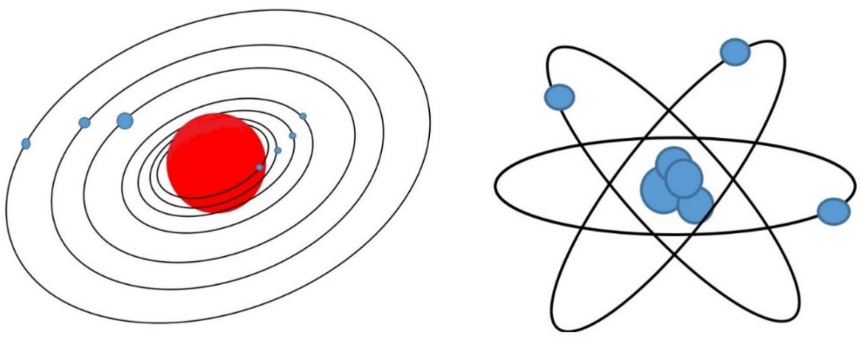


Figure 3.1. Comparison of relations in solar system and atom system (Gentner, 1983)

It is noteworthy that, within both systems, two pairs of interconnected relations exist. Firstly, in the solar system, the attractive force and the distance between sun and planets are interconnected, thus any alteration of either relation will lead to alteration of the other; also interconnected is the mass difference of sun and planets and the revolving movement between them. Secondly, in the atom model proposed, the attractive force and the distance between nucleus and electrons are interconnected, thus any alteration of either relation will lead to alteration of the other; also interconnected is the electric charge difference of the nucleus and the electrons, and the revolving movement between them. The principle of systematicity is applied in the analogy from the solar system to the atom model. Firstly, the interconnected relations are prior to the isolated relations. For instance, in the solar system one isolated relation is LARGER THAN (sun, planet), which is not preserved in the analogy. Secondly, the relations of objects in a system are prior to the attributes of objects when being mapped over. For instance, in the solar system attributes HOT (sun) and ROUND SHAPE (planets) are not mapped over in the analogy. The complete set of systematic mapping structure is illustrated in Figure 3.2 by heavy lines (French, 2002).

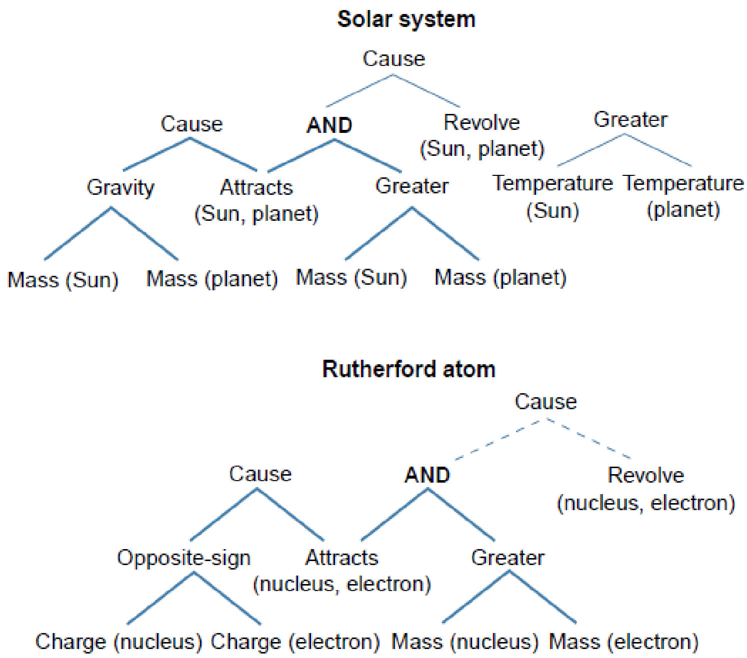


Figure 3.2. Mapping structure between Solar system and Rutherford's atom model

An interesting phenomenon of the analogy from the sun-planets system to the nucleus-electrons system is that although interconnected relations are mapped over, no higher-order relations are analysed or applied to the mapping. For instance, one second-order relation of ACCELERATION [REVOLVING MOVEMENT (planets, sun)] has not been preserved for mapping in the sun-planets system; neither has another second-order relation ALTERATION [ATTRACTIVE FORCE (sun, planets)]. There are two reasons for this phenomenon: 1) Although in theory the higher-order relations are prior to lower-order relations for mapping, the corresponding higher-order relations do not always exist in the target domain; and 2) From the perspectives of structures of both base domain and target domain, the interconnected relations are preferable to the isolated higher-order relations, as they more fully describe the structure of systems.

An example to demonstrate the application of SMT in the establishment of analogy would be the task of explaining the structure of the arterial system within the human body. An analogy could be established from a road transport system as the base domain to the target domain of the arterial system. The first-order relations from base domain include [DRIVE (vehicle, road)] and [DELIVER (vehicle, passenger)]. The corresponding first-order relations in target domain are [FLOW (blood, artery)] and [TRANSFER (blood, nutrition)]. It would be reasonable to assume that the human arterial system could be easily understood with the assistance of analogy than without.

It was argued by Gentner and Markman that 'similarity is like analogy', in the sense that the structure-mapping of analogy could be extended to describe similarity (Gentner, 1997), with the space of similarity and analogy illustrated in Figure 3.3.

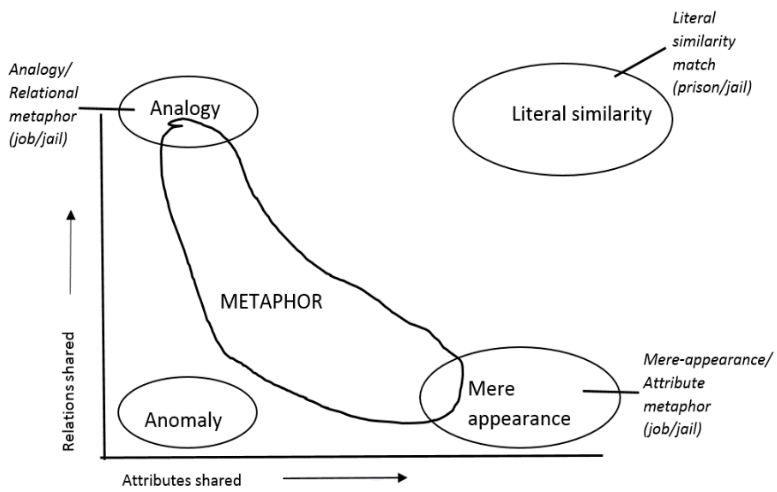


Figure 3.3. Comparison of space of literal similarity and analogy

Although the subsequent versions of SMT attempt to introduce additional constraints and conditions in order for broader interpretation of systematicity (Law et al., 1994, Forbus, 2000), the principles remain unchanged. The largest merit of SMT, despite its successful application in explaining the rules of analyses and establishment of effective analogies, is that it looks into the phase of mapping from a base domain to target domain from the perspective of structure. It provides a novel starting point for analyses of analogy. However, the focus on structure can be a double-edged sword, in the sense that systematicity does not always lead to plausibility, especially when all the concentration is laid on structure so that the backgrounds of domains may be neglected. Alteration of plausibility does not necessarily relate to systematicity, and occasionally the reduction of systematicity may lead to more plausibility (Jeong et al., 2008). Furthermore, the desirable higher-order relations from the base domain may not always have corresponding higher-order relations in the target domain, which would be another caveat that concentration solely on structure would cause. For instance, in the solar system, second-order relations such as the acceleration of revolving movement and the alteration of attraction force cannot be mapped into target domain, at least from the analogical perspective. Another setback of SMT due to systematicity would be that it may not be capable of mapping in an object-rich context (where quantity of objects exceeds quantity of relations), for instance the domain of mathematics in which real numbers could easily outnumber relations (Schlimm, 2008).

SMT plays undoubtedly an important role in research on analogy, as it focuses on analyses of the relations between objects that can be transferred successfully into large number of potential analogies. However, when analogical thinking is being applied, it may well be essential to consider the background and context of both domains, as structure can make little sense, especially for domains with huge attributes of objects (Bartha, 2013). Latest research adopting SMT include exploration for analogical inspirations based on analyses of component, behaviour and material content of given data, while highlighting the structural form of such analogical inspirations (Song and Fu, 2019).

3.2.2. Multiconstraint theory

As a further development of SMT, the Multiconstraint theory was introduced with the aim of exploring analogy as a cognitive process, and three basic types of constraints are included: similarity, structure and purpose (Holyoak and Thagard, 1989, Holyoak and Thagard, 1997). The Multiconstraint theory also acknowledges analogical mapping as the core of analogical cognition, and the structure of relations in both base and target domain plays a vital role in mapping, as described in the SMT. However, in addition to the structural constraint, both pragmatic and semantic constraints are taken into account when an analogical mapping is established, as described in Table 3.3 (Hummel and Holyoak, 1997).

Constraint type	Content

Structural constraint	Structural consistency: the correspondence between the source and the target elements should be consistent, regardless of context.
	One-to-one mapping: the correspondence between elements of the source and the target domain should be unique.
Pragmatic constraint	Mapping should be purposeful and preferred elements are deemed to be important to the reasoning goal.
Semantic constraint	Mapping of elements should consider semantic similarities between the source domain and the target domain.

Table 3.3. The three types of constraints in Multiconstraint theory

The pragmatic constraint requires the thinker to have approximately pre-defined purpose for the analogy, thus analogical mapping will take place under the guidance of the desirable direction. The semantic constraint provides larger flexibility for mapping, as the similarity of elements of both domains is taken into account. Multiconstraint theory enhances the criteria of analogical mapping by structural similarities, as its elements of pragmatic and semantic constraints regulate extra purpose and similarity between the source domain and the target domain (Barnes and Thagard, 1997). The effectiveness of allegories for purposes such as education, entertainment and political agitation is better understood when using Multiconstraint theory for analogy (Thagard, 2011). The most significant development of Multiconstraint theory compared to SMT is that, with the implementation of pragmatic and semantic constraints, more feasible analogical mappings are likely to emerge rather than with only the structural constraint. Multiconstraint theory not only provides extra guidance at finding appropriate mappings, but also improves the situations where correspondences cannot be established by analysing relations only in both domains (Bartha, 2013). Based on the essence of Multiconstraint theory, explorations have been made to establish a framework of connection for analogical reasoning between cognitive science and computational applications, by the means of abstraction and generalisation; while the value for such exploration needs further support from evaluation (Abdelfattah and Krumnack, 2019).

This chapter so far has organised a journey through the strategic literature review on the definition of analogy and the main theories of analogy; along with the subsequent sections on cognitive process of analogy and analogy in research and design, the chapter has accumulated insights together building up towards the identification of a research gap in the field of analogy. The literature review aims to not only present the background of analogy, but also justifiably leads to the proposed further work based on the obtained understanding of analogy.

3.3. Cognitive process of analogy

Research on the cognitive process of analogy discloses the insights of how analogy is established between the source and the target domain, and then achieves the knowledge transfer from the familiar to the unfamiliar. A selection of cognitive processes of analogy is analysed and illustrated in Table 3.4. An in-depth understanding of cognitive process of analogy plays an important role in both the general research of analogy (Vosniadou, 1989, Gust et al., 2008, Wagemans, 2018), and the utilisation of analogy with computational approaches (Hall, 1989, Gentner and Forbus, 2011, French, 2002, Linsey et al., 2012, Abdelfattah and Krumnack, 2019).

Source	Cognitive process
(Hall, 1989)	1. **Recognition** of a candidate analogous source, given a target description; 2. **Elaboration** of an analogical mapping between source and target domains, possibly including a set of analogical inferences; 3. **Evaluation** of the mapping and inferences in some context of use, including justification, repair, or extension of the mapping;

	4. **Consolidation** of the outcome of the analogy so that its results can be usefully reinstated in other contexts.
(Vosniadou, 1989)	1. **Retrieving** a source system (Y) which is similar to X in some way; 2. **Mapping** a relational structure from Y to X; 3. **Evaluating** the applicability of this relational structure for X.
(French, 2002)	1. **Recognition** of a source, given a target description; 2. **Elaboration** and **Evaluation** of the mapping between the two; 3. **Transfer** of information from the source to the target; 4. **Consolidation** (i.e. learning) of the outcome.
(Kokinov and French, 2003)	1. **Representation-building**; 2. Analogical **Retrieval** from the base domain; 3. **Mapping** from the base domain to the target domain; 4. **Transferring** new knowledge into the target domain; 5. **Evaluation** of applicability of the knowledge transferred; 6. **Learning** new insights from analogical thinking.
(Casakin, 2004)	1. **Identification and retrieval** of subjects that identify and represent the target situation within source domain; 2. **Mapping and transference** of established correspondences between objects and between relation among objects from the source domain to the target domain.
(Gust et al., 2008)	1. **Retrieval** of understanding of the situation from memory and adaptation; 2. **Mapping** of relations between the source domain and the target domain; 3. During the **Transfer** phase, the analogical relation is to translate information between the two domains.
(Gentner and Forbus, 2011)	1. **Retrieval**: Given a situation, find an analogue that is similar to it. 2. **Mapping**: Given two situations, align them structurally to produce a set of correspondences that indicate 'what goes

	with what,' candidate inferences that follow from the analogy, and a structural evaluation score which provides a numerical measure of how well the base and target align. 3. **Abstraction**: The results of comparison may be stored as an abstraction, producing a schema or other rule-like structure. 4. **Re-representation**: Given a partial match, people may alter one or both analogues to improve the match.
(Linsey et al., 2012)	1. **Encode** the source analogues stored in human memory; 2. **Retrieve** the appropriate analogue from the source domain; 3. **Map** from the source domain to the design problem as the target domain; 4. **Inferences** as design solutions are generated based on the mapping.
(Moreno et al., 2016b)	1. **Problem re-representation/reframing** enhances the development of solutions for the design problem by enabling a divergent mindset; 2. **Provide analogies**/provide analogies with open design goals through analogical mapping and transferring.
(Gentner, 2012, Gentner, 2018)	1. **Retrieval**: a person may be reminded of a prior analogous situation by a current topic in long-term memory. 2. **Mapping**: involves a process of aligning the representations and projecting inferences from one analogue to the other. 3. **Evaluation**: the analogy and its inferences are judged once an analogical mapping is established.

Table 3.4. A selection of cognitive processes of analogy

It is apparent that all the representative cognitive processes of analogy entail three key phases pre-, during-, and post-analogical mapping i.e. retrieval, mapping and abstraction. Retrieval involves identifying a set or several sets of relations as analogues within the source domain; mapping is the key phase which entails analogical mapping of relations between the source domain and the target domain and the transfer of such relations; abstraction happens as the result of analogical mapping and produces a schema or solutions to the problem. It has been argued by some researchers that learning is also necessary phase in the process as it represents the goal of analogy of achieving new knowledge (French, 2002, Kokinov and French, 2003). This view is echoed with by proposal of processes with phases of consolidation or 're-representation' (French, 2002, Gentner and Forbus, 2011). A generalised cognitive process of analogy can be illustrated as Figure 3.4, based on the comparison of mainstream analogy processes.

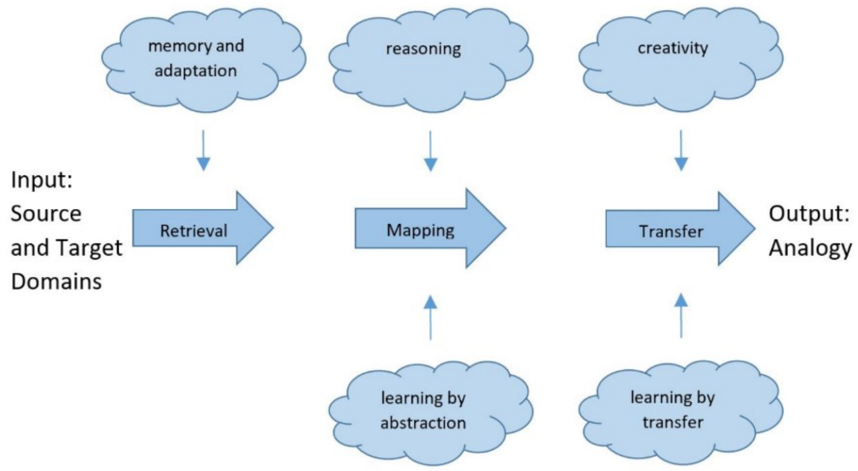


Figure 3.4. A generalised cognitive process of analogy (Gust et al., 2008)

The study of cognitive process of analogy has provided structured guidance for computational analogy (see Section 3.5). However, more insightful research is necessary to enable analogical thinking to enhance design, as the better structured representation of system helps the identification of structural similarities between the domains and hence generate analogies (Vosniadou, 1989).

3.4. Application of analogy in creativity tools

Since analogy plays a vital role in the fundamentals of cognitive science, it is natural that analogy is embedded broadly and deeply in creativity. Creativity is defined as the act of making new relationships from old ideas (Schlesinger, 1980), the ability to look at things differently (Oneill, 1990), or as an act that produces effective surprise (Curry, 1972), or in many other ways (see section 2.1.1).

Creativity tools are powerful aids to creativity; they are designed to help the users follow more effective pattern towards creativity and thus creative solutions are more likely to achieve. In the realm of creativity, analogy usually exists as either or both of the two following roles: 1) Analogical thinking as a reasoning methodology is like one of the commonest 'Lego blocks', which is compulsory for building and also fits in multi roles and 2) The relation between analogy and creativity can be considered as that between a screw driver and a tool box, as analogy can be widely embedded in numerous creativity tools towards the stimulation of creativity. Analogical thinking as an effective methodology is recommended in general creative processes, but the most significant applications of analogy, in the sense of analogy as fundamental, can be found in creativity tools such as TRIZ (SLP), Synectics, and Biomimetics.

3.4.1. Analogy in TRIZ (SLP)

The SLP (smart little people) method breaks a problem down into different elements and sees the elements from views of imaginary tiny beings, who are smart as they have ability to analyse and solve problems but also little as there are no limits to size (Gadd, 2011). The fundamental of SLP approach is the creation of the smart tiny being, where both personal analogy and fantasy analogy are utilised. The SLP stands for a typical value of analogy in creativity, where focus is on the use based on a given analogy. As a part of practical application of analogical thinking, SLP is adopted in the case study of enterprise design in Chapter 8. A similar type of use of analogy can be found in Super Heroes, where personal analogy and fantasy analogy are again pre-defined before the problem-solving phase (Grossman, 1985). This type of application of analogy in creativity tools is capable of triggering creative ideas, but it would be sensible to conclude that, since little analogical mapping is established, it is the concept of analogy that leads to creativity, rather than analogical reasoning.

3.4.2. Analogy in Synectics

Synectics provides structured guidelines to adopt analogical thinking towards idea generation. The aim of analogies is integrated in the two mechanisms: making the strange familiar and making the familiar strange (Gordon, 1961). The key element of Synectics is analogy, which "is the process of recognizing similarities between dissimilar things; a form of cross-referential thinking wherein things from one classification or subject realm can be related to that of another" (Roukes, 1988). Synectics helps stimulate creativity in design (Jia et al., 2018). By iteration of jumping between the familiar and the strange, novel connections can then appear and new ideas are likely to emerge.

All types of analogies could be utilised in Synectics, including direct analogy, symbolic analogy, and personal analogy, depending on the thinkers' knowledge, experiences, and styles. In contrast to the application of analogy in SLP, no pre-defined analogies are introduced, and little restriction should be applied in Synectics. The 'freewheeling' style of thinking encourages the sparking of innovative ideas, similar to brainstorming. The outcome of using Synectics heavily depends on participating thinkers, as although analogical thinking is required, no mechanism is transferred to the thinkers as to how to think analogically. Ideally sufficient pre-session trainings are provided, where the theories and models of analogical thinking are introduced, such as SMT and Multiconstraint theory. The analogical keynote enables Synectics as an effective tool to enhance the students' creative thinking in a comparison study (Aiamy and Haghani, 2012). A analytical review of Synectics as a creativity tool is illustrated in Section 2.3.4.

3.4.3. Analogy in Biomimetics

Biomimetics endeavours to find corresponding phenomena and solutions to engineering problems from the vast resource in biological world, by establishing suitable analogies between these two domains (Vincent et al., 2006). Biomimetics is a relevant new word, as the first-known dictionary definition in Merriam-Webster dictionary in 1970 is 'the study of the formation, structure, or function of biologically produced substances and materials (such as enzymes or silk) and biological mechanisms and processes (such as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones' (Merriam-Webster, 2019). Although Biomimetics as a research subject is relatively new, biologically inspired designs have existed for much time. For instance, as illustrated in Figure 3.5, George de Mestral invented Velcro after investigating the burdock root seeds that became attached to his dog after being walked outdoors (Christensen and Schunn, 2007).

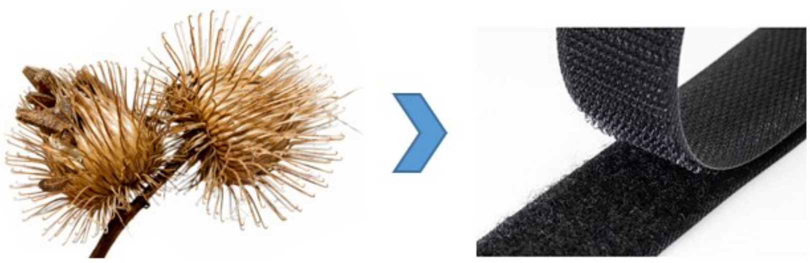


Figure 3.5. Biologically inspired invention of Velcro

(Picture source: https://inlanding.wordpress.com/2013/11/19/flora-along-the-oxford-canal-burdock/

https://www.seattlefabrics.com/Nylon-Sew-on-VELCROreg-Brand-Fasteners_p_444.html)

In the literature, the "biologically inspired design or adaption or derivation from the nature is referred to as biomimetics" (Bhushan, 2009). Biomimetics has also been referred to as Bionics, Biomimicry, biological design, and bio-inspired design (Vincent, 2009).

The use of analogy in Biomimetics is a combination of that in SLP and Synectics, in the sense that the base domain of analogies is pre-defined as the biological world; while which phenomena to choose for analogical mapping, or even what level of biological phenomena to choose is yet to be decided. These decisions will be made by the thinkers based on own knowledge and experiences, and assistance could be obtained by a general search, searching a biological database and asking for advice from biologist(s) (Shu et al., 2011). Since the base domain of biological world has been pre-defined, Biomimetics is more likely to be used as a problem-driving approach for problem solving. Analogy plays the essential role at the transfer of wisdoms from biology world to engineering world. In analogy, it is not the attributes of the systems in the source domain that determines the transfer, but the relations within the systems. Thus, until a potential prototype or phenomenon in biology has been studied and understood, simple and direct replicas from biological domain to engineering domain can rarely be successful. In order to match the hierarchical structure of biological phenomena, it is necessary to follow a structural creative process.

Biologically-inspired design has attracted research interests where analogical thinking is applied and biology is chosen as the source domain to solve problems in the target domains of engineering or other design domains (Vincent and Mann, 2002). Ask Nature is another attempt as an online tool for designers and the public to access the database of the biological world to become inspired and generate ideas through analogical mapping from the biological domain to domain of problems (Ralevski, 2006). However, due to a lack of understanding of biological knowledge or of the mapping process from biological world to engineering and design realm, the analogical mapping with the biologically-inspired design suffers from limited effectiveness (Vattam et al., 2010, Vincent, 2009). Biologically-inspired design aims to enhance design by transferring inspirations acquired from the biological domain, and such transfer can be initiated both ways by problem-driven and solution-based approaches. The problem-driven approach first defines the design problem in the technological domain and then endeavours transfer towards solutions from the biological domain; while the solution-based approach analyses the functions in the biological domain before analogically abstraction towards application in the technological domain (Badarnah and Kadri, 2015). In order to enable more effective design outcomes through biologically-inspired design, the collaboration between engineers and biologists in exploring both domains need to be inspirational to both domains (Salgueiredo and Hatchuel, 2016).

Biomimetics is a huge research topic with significant potential that nature enables to enhance artificial mechanisms and design. Thus, this section aims to reflect the research approach of Biomimetics and its enhancement to design relevant to this study, rather than providing a comprehensive review of Biomimetics. The following analysis of Bhushan's description of spiderweb would offer a general angle of how Biomimetics can benefit design through analogical thinking (Bhushan, 2009, p.1475).

"Spiders ***produce*** *a variety of proteins, among which are major ampullated silks (MAS). MAS fibres are used by spiders as a scaffold upon which they* ***attach*** *other silk fibres during the formation of the web. The spider* ***generates*** *the silk fibre and, at the same time, is* ***hanging*** *on it. It has a sufficient supply of raw material for its silk to* ***span*** *great distance; Spiderweb is a structure* ***built*** *of a one-dimensional fibre. The fibre is* ***very strong*** *and* ***continuous*** *and is* ***insoluble in water****. The web* ***can hold*** *a significant amount of water droplets, and it is* ***resistant to*** *rain, wind and sunlight. Spider silk is*

three times stronger than steel, having a tensile strength of approximately 1.2 GPa. Some spider silks have ***high stiffness*** *with a tensile modulus of approximately 10 GPa, while others are* ***elastomeric*** *with a modulus of approximately 1 GPa and an extension to rupture of 200 percent. The combination of* ***strength and extensibility*** *is primarily derived from the domains of crystalline β-sheets and flexible helices with the polypeptide chain, imparting a toughness that is greater than bone, Kevlar and high strength steel. The web is designed to* ***catch*** *insects (food for the spider) that cross the net and get* ***stuck to*** *its stickiness and complex structure* (Bhushan, 2009, p.1475)*"*

This text describes the natural attributes and structural properties of the spiderweb, as well as its functions. Highlighted key words form an essential understanding of knowledge about spiderweb, which is elaborated by quantitative technical data from scientific research. The description reflects the retrieval of information available about the analogue of spiderweb in the source domain of nature. According to the cognitive process of analogy, the retrieval phase is the foundation of the subsequent mapping and transfer as it provides information of relations of the chosen analogue.

"While mechanical properties of the web fibre are remarkable, it is also quite interesting how a spider creates a two-dimensional web out of its silk fibre. Krink & Vollrath ***analysed*** *spiderweb-building behaviour using a* ***computer model*** *that* ***constructed*** *artificial webs with a* ***rule-based simulation****. They found that web characteristics, such as the spiral distances, eccentricities and vertical hub location, were* ***accurately simulated*** *with the model. They later proposed a 'virtual spider robot' that builds virtual webs, which perfectly* ***mimic*** *the* ***visual architecture*** *of real webs of the garden cross spider uses* ***web-building decision rules*** *that are strictly local and based on the interactions with previously placed threads to* ***generate*** *global architecture. This may be interesting for the modelling of* ***biological self-assembly*** *of complex material from the local rules to the overall structure that is* ***adaptive*** *to the external conditions. Researchers have used the* ***synthesis of structural proteins*** *to produce* ***polymers for fibres*** *that may become commercially useful in the future. Dzenis suggested an* ***electrospinning*** *technique to produce 2µm diameter* ***continuous fibres*** *from polymer solutions that are somewhat similar to the spider silk fibres."*

In this text, the mapping and transfer of the cognitive process of analogy occur, as indicated by highlighted phrases. In the first transfer application not only the morphological characteristics of the spider's web are transferred over but also the rules of web-building decision resulting the characteristics. In the second and further suggestions of application, the structural proteins are to be mapped over to the artificial synthesis as the subsurface cause of the polymers for fibres. The analysis of this example of spider's web indicates the analogical thinking behind Biomimetics, and the insights can be transferred over to benefit design. In practice, a comprehensive understanding of the biological source domain is essential when it comes to specific relations and phenomenon, and a systematic guidance to explore the source domain would be helpful to establish a sufficient understanding of suitable analogues.

The analysis of the key words from the above-quoted texts helps to derive the functions and relations from the semantic description within the source domain of biology. This is a language-based analogical method developed to identify the appropriate biological functions, mechanisms and phenomenon, which are to be mapped and transferred to solutions to engineering problems (Chiu and Shu, 2007, Shu, 2010). The analogical process follows the cognitive phases of retrieval, mapping and abstraction. The analysis of the key words, especially verbs, indicates the key functionalities that require analogical mapping to the engineering domain. A similar word-based method (Wordtree), which utilises semantic analysis and linguistic reasoning to achieve analogical mapping for design solutions, has also proved to be effective (Linsey et al., 2012). It is worth noting that the adoption of semantic analysis for searching potential analogical mapping should have universal value, regardless of the source and target domains. However, the methods of lexical analysis only provide a starting point to utilise Biomimetics due to the complexity of the biological world (Vincent, 2009). In addition, it is important to understand the requirements for users of such analogical design tools including, the skills and work styles of designers and their knowledge about biology (Yargin et al., 2018).

3.5. Application of analogy in academic research

Analogical thinking is useful as a process to solve a given problem by transferring the knowledge retrieved from a familiar problem. The primary use of analogical reasoning was transferring within the same domain (Bhatta and Goel, 1996). Functional analysis and similarity are the fundamental pillars of the use of quantitative function metrics in this research. However, design-by-analogy here works as a concept to describe the derivation of new designs from the analysis of similar functions from the existing designs, while analogical mapping between domains are concentrated on less (McAdams and Wood, 2002). A study on knowledge acquisition indicates that the ability to identify analogies and use analogy for problem solving in an unfamiliar target domain is observed from both adults and children; the analogies involved include within the same domain and between domains (Vosniadou, 1989). In the realm of general problem solving, to assist on the identification of suitable source of analogies from the base domain, animated sources have been observed with the ability to yield more analogical transfers, compared to diagrammatic or verbal analogue sources (Kubricht et al., 2017).

Computational analogy has been a popular approach to study and apply analogical thinking. A series of computational studies of analogy were reviewed based on an abstract process model for analogical thinking, and computational studies of analogy is predicted to develop into more mature states (Hall, 1989). Computational methods are adopted to enhance design-by-analogy. Computational coding is attempted to establish a formalism using analogical mappings at Function-Behaviour-Structure level so that analogy can be used to help produce new design from different design domains (Qian and Gero, 1996).

A review of over 40 computational programmes of analogy since 1960s indicates the limitation and possible future research on computational analogy, such as better representations of the situations in both source and target domains, a better understanding of the retrieval mechanisms of long-term memory, a better exploration of representation-building and learning mechanisms, and the integration of these mechanisms into analogy programmes then the scaling up (French, 2002). A following study attempts to categorise the computational models of analogy into symbolic, connectionist and hybrid types (Kokinov and French, 2003). The research on computational analogy could benefit from collaboration between psychology and Artificial Intelligence (AI), with contributions from linguistic and philosophic inputs; such computational models of analogy have different focuses such as capturing analogical phenomena at the cognitive level, and modelling implementation of analogy in neural systems (Gentner and Forbus, 2011). Compared to the analogical thinking by human, AI systems are deployed to enhance scalable analogical mappings between domains in design by tacking the challenges associated with fixation and complexity (Kittur et al., 2019).

Application of analogy in AI was reviewed by Goel as an important role in transferring knowledge about the existing situation to another situation. The generic abstractions required in analogical transfer would indicate the structure of relationships between objects or processes; design concepts, prototypes and patterns are identified as three analogy-based design theories that research of AI can benefit from (Goel, 1997). Analogy was embedded into the design of an APP supporting mobile creativity, which attempts to provide better care for people with dementia (Maiden et al., 2013). One function of the APP analogically matches a current situation to an expected care practice using base domains such as prison and parenting. SMT's relation mapping is applied to establish relational mappings from care domain to non-care domains. In another application of analogical thinking, the management of real-time parking space booking is investigated as the target domain, while mappings are set up from the base domain of existing hotel reservation web applications (Zachos and Maiden, 2008). Although in both these attempts there are various of limitations working against the initiatives, analogical thinking is proven as being capable of providing new ideas and potential solutions, given that the key relations are correctly mapped over from the base domain to the target domain. Further related exploratory research have been focused on the support of digital creativity to enhance professional applications, such as in journalism (Zachos et al., 2018, Maiden et al., 2019), and manufacturing (Maiden et al., 2017).

Another type of utilisation of analogy in creativity is to deliberately combine an analogical thinking phase into an idea generation practice. The advantages of this type of application include the following: 1) Thinkers are not required to have insightful understandings of mechanisms of relation mappings, and analogical thinking can still occur even if good examples of analogy are properly introduced. 2) The phase of analogical thinking can be independently embedded into an ideation session, especially when flexibility is required. One such typical application is Professor Horri's workshop of experience design for behavioural change at the Royal College of Art, as is reported in Appendix 2.

3.6. Conclusions

The insights generated in this chapter include essential understanding of analogy through a comparison of definitions of analogy in dictionary and academic literature, a strategic summary of main theories and cognitive process of analogy in cognitive science, and the identification of analogy in a selection of key creativity tools. Analogy is about successful mappings from the base domain to the target domain, and through which knowledge is transferred. It is reasonable to believe that analogy would play as important roles in creativity and design as in existing subjects of application, provided that the mechanisms of analogy are understood and that its process is well-established in the contexts of creativity and design. The most widely recognised theories on analogy base on the mappings with structural, pragmatic and semantic constraints. In the context of design, effectiveness of analogical thinking could be indicated by the quality and quantity of designs, the ease of design process with analogical thinking embedded, and the subjective feelings of the designers.

As determined in the research methodology described in Chapter 4, the strategic literature review on creativity and analogy provides the study with essential understanding of relevant fields, contributing to a focused Initial Reference Model which helps to shape the study direction as illustrated in Figure 3.6 (Blessing and Chakrabarti, 2009). This Initial Reference Model reflects the organised review for understanding and helps shape the research direction by focusing on key relationships between modes. As the study progresses, further understanding is acquired and would lead to an updated Reference Model.

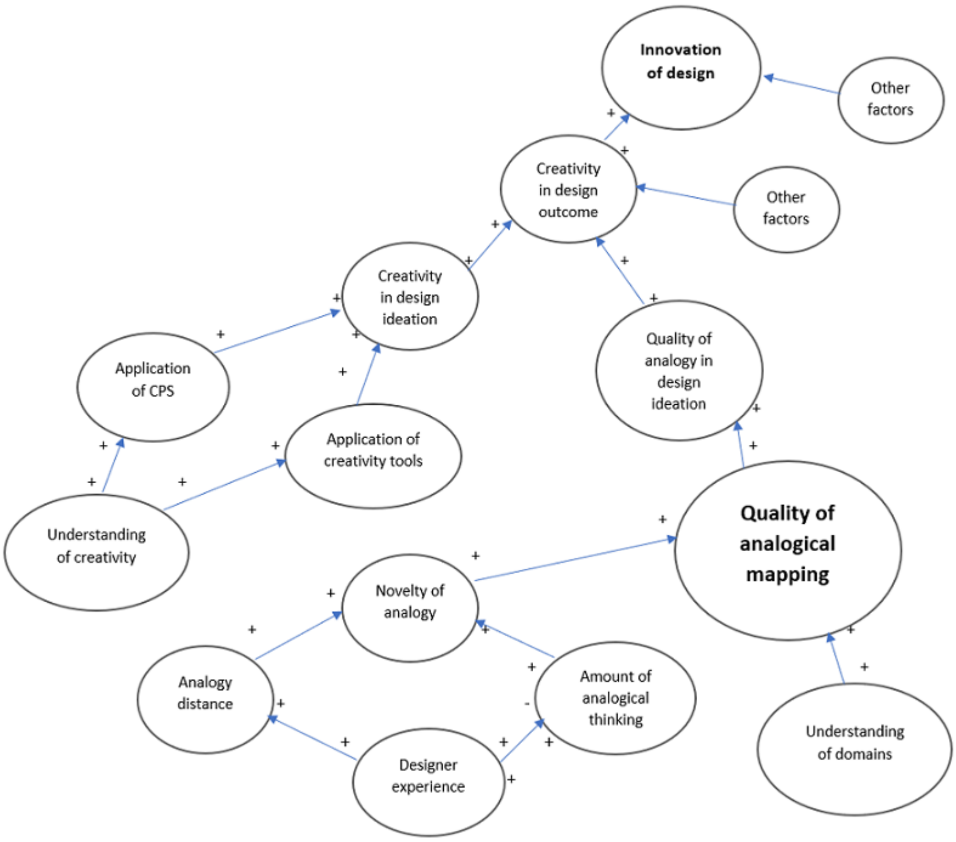


Figure 3.6. A focused Initial Reference Model for study

The quality of analogical mapping has been identified as the preliminary key factor for conducting the study, with the enhanced innovation of design as the preliminary success factor. An Initial Impact Model, as illustrated in Figure 3.7, has been developed on the basis of the focused Initial Reference Model, with clear identification of the interest in this study regarding systematic methods to assist analogical thinking so that the quality of analogical mapping can be improved. Both models aim to reflect the key elements involved in this study, rather than detailed factors, to identify the most essential research outcomes expected.

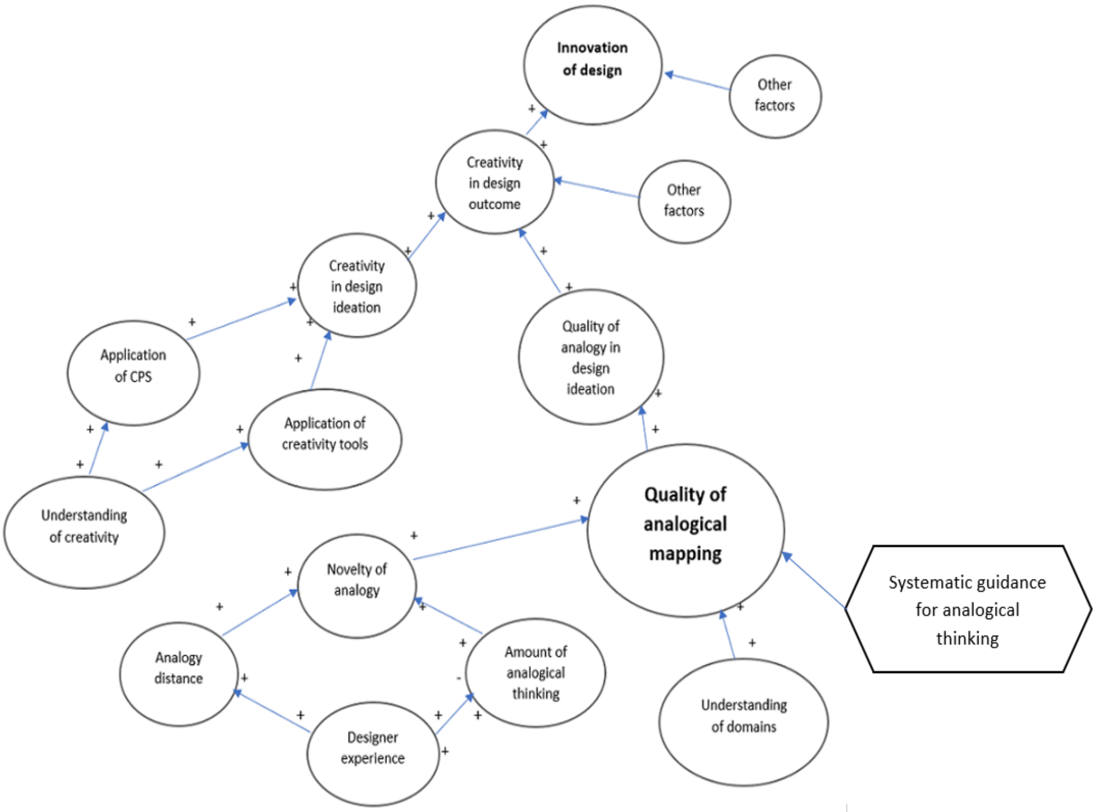


Figure 3.7. An Initial Impact Model for study

The application of analogy can be recognised within typical creativity tools such as TRIZ(SLP), Synectics and Biomimetics. However, it seems to be the idea of analogical thinking rather than its actual procedures which is heavily concentrated in these tools, even in Synectics where the key mechanism is to apply analogical thinking. Therefore, the establishment for applicable and efficient guidance through which analogical thinking is better exploited would stand for more significant meanings in the realm of application of analogy in creative design. A developing trend of application of analogy is to combine the logic with computational algorithms such as mobile applications, which assist in generating analogical ideas or solutions without requiring users' knowledge or training on analogical thinking.

Analogy is widely adopted in design contexts, especially for creative ideation in the conceptual design phase. The biological world has been used as a suitable source domain to establish analogical mappings for problems in other domains. Findings on whether engineering designers would utilise analogy without intention would be useful in understanding the acceptance of analogy's value. The comparison between analogy and existing creativity tools on the effectiveness of creative ideation would be just as meaningful as a comparison between analogy and non-analogical thinking. Design by analogy is a popular research field and many studies have been conducted on the impact of analogy distance in design and the difference in use by expert and novice designers with analogy. More research on systematic analogical thinking is suggested in the creative design process, so that design can potentially benefit more from the strength of analogy. These knowledge gaps lead to the research activities in the empirical study in Chapter 6, where answers to the raised research questions will begin to be developed.

Chapter 4. Research methodology

This chapter outlines the research methodology for the whole study, with the introduction of key research aims and contents of each phase within the methodology. Research rationales and key research activities are further elaborated chapter by chapter so as to guide the flow of study. The selection of research methodologies and research methods are discussed with indication of merits and demerits, along with consideration on research ethics and quality.

4.1. Overall research methodology

4.1.1. Framework for overall research methodology

The Design Research Methodology (DRM) illustrated in Figure 4.1 (Blessing and Chakrabarti, 2009) has been adopted in this research to ensure a comprehensive and systematic approach to find answers to the research questions and implement research activities. This research does not attempt to follow the DRM in a total linear and rigid fashion. Instead, feasibility and flexibility are sought within the DRM framework. Iterations and reflections are encouraged between each phase at implementation. Overlapping of important contents such as evaluation is allowed between adjacent phases for a more natural flow in practice.

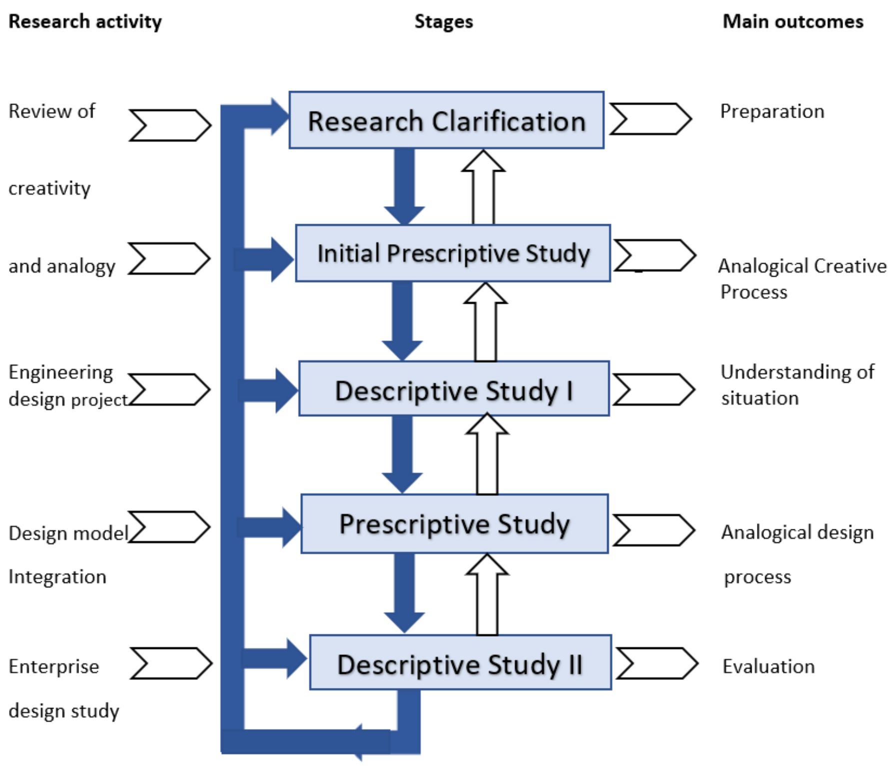


Figure 4.1. DRM framework as research methodology

This research strives for the enhancement of creativity in design by analogical thinking. Three sub-systems are involved in the study: to discover the value of analogy in creativity; to investigate the application of analogical thinking in creative design process; and to study the utilisation of such application in the real-world project of enterprise design.

The overall research methodology for this study and research methods in each chapter are introduced. Methodology here means the set of methods and tools which form the overall framework for conducting the research, whereas methods are specific activities undertaken to improve research. The Research Clarification phase updates the researcher's knowledge database in the setting of this study, which is concerned with the information on creativity, creativity tools and analogy. An up-to-date overview of the existing knowledge on analogy and its application in design needs to be established, and therefore, in the Descriptive Study-I phase, an empirical study of the application of analogy in a real-world engineering design project is carried out. The outcome provides the subsequent Prescriptive Study phase with practical data and in-depth understanding, so that combined with the exploration of further literature reviews and interviews, a model describing a desired situation of creative design process can be developed. The outcome of Prescriptive Study offers the support for improvement of design by introducing an analogy-empowered creative design process. However, it is necessary to evaluate the proposed model on its applicability and usefulness. The Descriptive Study-II phase examines the research outcome so far by a case study in the setting of enterprise design, so that any possible contribution for the design of enterprise from the developed support for creative design can be identified and initially evaluated. The overall research methodology incorporated with research activities and outcomes from key chapters is illustrated in Table 4.1.

Chapter	Content	DRM phase	Outcome
2	Literature review of creativity and creativity tools	Research Clarification	To establish insights of human creativity and the mechanisms of creativity tools
3	The review of analogy, its theories and use in creativity	Research Clarification	To understand the attributes and structure of analogy; and to identify the initial reference and impact models
5	Analogical Creative Process (ACP) proposal	Initial Prescriptive Study	To provide the following studies with a new method of ACP featuring the cognitive theories of analogy
6	The comparison of analogical thinking and existing creativity tools in conceptual ideation of an engineering design project	Descriptive Study I	To harness in-depth understandings of the value of analogical thinking, in the setting of a practical engineering design project
7	The proposal of a model for the design of enterprise with analogy as one	Prescriptive Study	To propose a model for creative design embedded with analogical thinking, which is

	module, based on data from literature review, semi-structured interviews and review of fellow researchers' work		potentially applicable in enterprise design
8	The application of analogical thinking in an enterprise design project of a start-up business	Descriptive Study II	To obtain a data outcome from an initial evaluation of analogical thinking in the design of enterprise practice

Table 4.1. Illustration of research methodology and activities

This study aims to discover new insights about creativity and analogy from existing research, as well as developing original and useful tools from such insights to contribute to future research and application in the domain of design. To achieve this, the input of research effort needs to be optimised according to the available resource and prioritised towards certain phases. The type of research activities varies in each research phase, based on the research aims, the goals of deliverables, and the available time and resources. In addition, the research scope and focus are maintained throughout the whole study, as distraction and diversion could comprise the main focus of this research.

The Review-based study consists of the strategic literature review of research topics and domains. It aims to provide the researcher with essential knowledge of the existing information that is available, and to help the researcher to identify any knowledge gaps and determine initial research questions. Creativity and analogy are reviewed in this study and Analogical Creative Process is developed from the theories of the establishment of analogy.

The Comprehensive study includes both a literature review of existing studies and the researcher's own study, which is designed to gain an in-depth understanding of chosen topics and to develop support for creative design with evaluation, depending on which phase the Comprehensive study is conducted. The Comprehensive study in Descriptive Study-I reports the value of analogy in the conceptual design of a real-world engineering design project. The Comprehensive study assisted by the review in the Prescriptive Study phase develops support for creative design, where an analogy-empowered creative design process is proposed to be integrated into a model for the design of sustainable enterprise, with the assistance of data gathered from the literature review and interviews.

The Initial study investigates the application of previous research outcome to indicate early-stage results, and to prepare the results for future studies. An Initial Descriptive Study-II is conducted in a practical fashion, where applicability evaluation of analogical thinking in the design of enterprise is carried out by a real-world project of developing a technology start-up company.

4.1.2. Brief introduction to each phase within research methodology

As illustrated in Table 4.1, the Research Clarification (RC) phase includes a literature review of creativity, creativity tools and analogy. Creativity is understood as the act to make new relationships from old ideas, while creativity tools are the techniques derived from theoretical or empirical studies to enhance creativity. Investigation of creativity tools indicates that analogy, as an effective way for new connections, can be identified in a selection of creativity tools such as TRIZ, Synectics, and Biomimetics. Further reviews of analogy disclose its potential to be adopted to boost creativity in design activities including engineering design and the design of enterprise.

The Initial Prescriptive Study (IPS) followed RC directly aiming to propose the method of Analogical Creative Process, which is derived from the theories of cognitive process for analogy. The clarification and analyses established knowledge gaps and research questions, which helps to form the overall research plan. The new method is to be applied in studies reported in following chapters to observe its functions through evaluation.

Descriptive Study I (DS-I) attempts to harness in-depth understanding of analogy's value in conceptual ideation of an engineering design project. Together with the outcome from the previous literature review, the empirical study at this stage forms a comprehensive study that discloses further insights into analogy's value in a practical project. In addition, the DS-I phase also indicates that there could be potential for analogy and analogical thinking to be embedded in design processes in order to enhance creativity for design. This assumption has been testified by the outcome of a subsequent case study, but further efforts are needed in order to develop this discovery into realistic support for improved creative design.

The Prescriptive Study (PS) phase aims to elaborate on the collection of insights obtained by both literature review and empirical study from previous phases, and to improve the research basis by developing support for creative design for the improvement. It is the key phase to creatively envisage and develop new knowledge based on previous understanding. Reasonable assumptions are made to elaborate from the available evidence. This research chooses to conduct a comprehensive PS i.e. the PS is undertaken with the assistance of existing literature review and the knowledge source that is available to the researcher as existing support, and then assumptions are made based on both the literature review and the researcher's own exploration through empirical study towards a design process featuring analogical thinking.

Descriptive Study II (DS-II) evaluates the improvement support developed by PS, and thus forms an important part of the utilised methodology framework. This research decides to conduct initial application evaluation for the applicability and usefulness of the developed support. Application evaluation focuses on the evaluation of applicability of the support by PS. DS-II in this research adopts Action Research as evaluation approach for the case study and aims to demonstrate the/an initial DS-II evaluation due to the constraints on time and available resources.

4.2. Research rationale, methods and key activities by chapters for RC (IPS), DS-I, PS and DS-II phases

4.2.1. Research rationale and key activities in RC and IPS phases

The RC phase in this research involves the strategic literature review on creativity and analogy. The initial aim for RC phase was to gain essential knowledge on creativity, creativity tools and analogy with the hope of being able to identify knowledge gaps suitable for further exploration. Figure 4.2 illustrates the key activities within the RC and IPS phases. The rationale behind the key activities is not linear or rigid, but keeps elaborating as the scope of understandings grows. The boundaries between each group of key activities are not meant to be clear, and as iterations happen within the RC phase, the existing understandings and initial decisions keep getting refined by new developments.

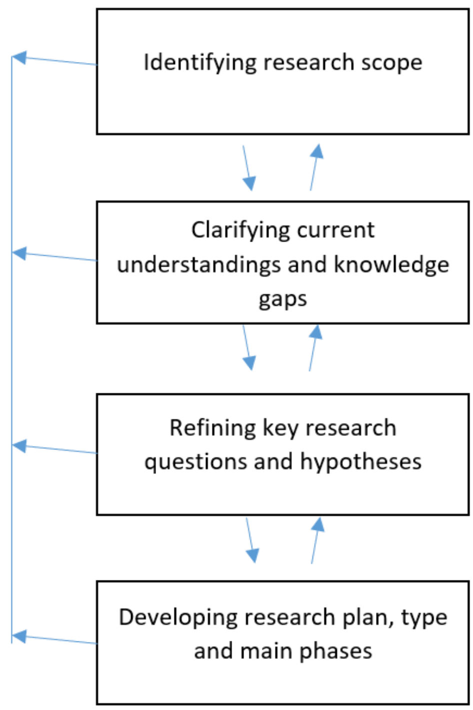


Figure 4.2. Rationale and key activities within RC and IPS phases

The most challenging task within the RC phase is to identify feasible knowledge gaps based on the understandings of existing situation of relevant research. The knowledge gaps, which tend to be overlooked by the existing research, are suitable to explore given the identifiable resources and are realistic within the scope and depth of a doctorate level research project. To tackle this challenge, a set of research methods are adopted. The literature review forms the largest percentage of research activities through RC phase and helps identify the research scope and building knowledge framework for the research topics. Communication with other academics and researchers has been proven to be valuable in identifying strategic direction, in particular the suggestions received from the supervisors are key promoters towards converging the research questions and directions. Participation in lectures and workshops on creativity and creativity tools offers guided understandings of topics of interest and helps to obtain practical experience in the use of creativity tools. In addition, several case studies as experiments were also conducted or participated in during the RC phase with the application of creativity tools to solve real-world design problems.

The IPS phase follows the RC phase directly as it is derived from both the analyses of cognitive theories of analogy and the observed lack of a systematic method for analogy to perform in design. It has been identified that, although the essence of analogy can be found in a selection of existing creativity tools, the structure of analogy has not been applied as a process for creativity to the researcher's knowledge. Furthermore, the analogy-empowered creative design process could have practical potential in real-world design domains including engineering design and the design of enterprise.

All the aforementioned methods and activities serve the purpose of the RC and IPS phases in this study, and contribute to the implementation of subsequent research phases, the outcome of which in turn feeds back into RC phase for more clarified research management. As a result, the initial overall research plan is not concrete or inflexible, as it aims to provide a strategic direction for the entire study and future adjustments are allowed to fulfil the requirements for more refined research questions.

4.2.2. Research methods and key activities in DS-I phase

The DS-I phase in this study aims to obtain in-depth understanding of the application of analogy in design practice. A comprehensive DS-I has been chosen, which involves a literature review of existing application of analogy in conceptual design ideation, followed by an empirical case study to complement the understandings. The key research activities are illustrated in Figure 4.3. It is worth noting that the reviewed literature relevant to DS-I phase includes existing application of analogy in design and introduction to existing non-analogical creativity tools for the comparison purpose within the case study. The arrows between each group of key research activities indicate the directions of implementation and feedback; the arrows pointing to the overall connection on the left indicate overlapping activities, and iteration between activities are allowed.

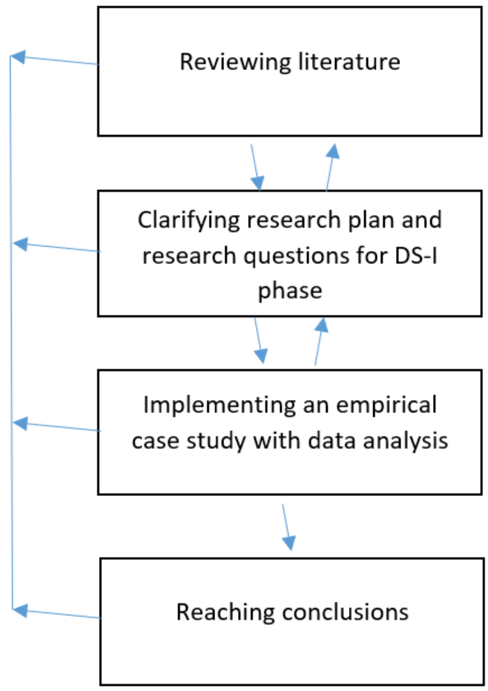


Figure 4.3. Key research activities within DS-I phase

Arising from the literature review of analogy reported in Chapters 3 and 6, a deficit in understanding the application of analogy in a design project is identified: the comparison between the value of analogy in conceptual design ideation and the value of existing non-analogical creativity tools is unclear. Therefore, a supplementary case study to solve this issue was planned within the setting of an available engineering design project. The clarified research question as illustrated in Chapter 6 is: How effective is analogical thinking in conceptual design ideation of a real-world engineering design project?

The effectiveness of creative ideation in conceptual design can be demonstrated by quantity, quality, novelty and variety of the ideas generated (Shah et al., 2003).

Engineering design is a “purposeful activity directed towards the goal of fulfilling human needs, particularly those which can be met by technological factors of our civilization” (Asimov, 1962, p.150). A real-world engineering design project would involve the process of realising the required technical functions of product by design activities. The answer to this research question is explored primarily in Chapter 6, based on the insights from the strategic literature review of creativity and analogy in Chapters 2 and 3.

For the conceptual design phase where organised ideation sessions are conducted, to better answer the research questions raised above, a method of sequential Mixed Methods Research (MMR) has been identified and applied. This study aims to identify correspondence and consistency from the findings and analysis of data, which then would evidently lead to a preliminary conclusion from triangulation. Furthermore, given the subjective nature of data gathered from creative ideation, this research is set to be qualitatively driven, although similar studies in the future would also benefit from data obtained by additional quantitatively driven approaches.

Without diverting excessive attention to the design of typologies of MMR, the overall structure of the MMR here is set to be an explanatory sequential approach (Creswell, 2009), where a quantitative data collection and analysis phase (ideation activities using non-analogical and analogical thinking tools) is followed by the harvest of qualitative findings from literature review and post-ideation survey for feedback, with the aim of identifying convergence and consistence in findings. The consistent findings from this study are therefore verified by triangulation, where similar data is collected using different methods (Denzin, 1989).

4.2.3. Key research activities and methods in PS phase

The PS phase aims to generate findings from the previous literature review at RC phase and empirical study at DS-I phase, and these findings can then be evaluated as potential support for design research as a theoretical outcome of this study. PS phase study forms an important part of the whole study as it transfers existing knowledge and understandings into new and useful insights for future use. This PS study can also be treated as an independent study to develop new methods from existing knowledge.

The research activities are organised in this PS phase as is illustrated in Figure 4.4. The process is again not meant to be linear or with clear boundaries between steps. Iteration and overlapping are necessary to aid the flow of the development of the outcome findings, as shown by arrows between steps indicating elaboration and feedback. All steps share common elements such as literature review and evaluation, as shown by the backbone on the left that all steps communicate with.

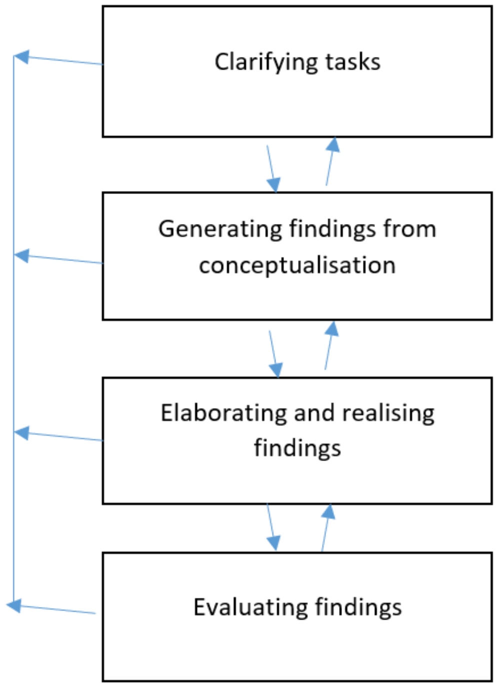


Figure 4.4. Key research activities within PS phase

To help clarify the tasks, a selection of design processes is reviewed and the commonality with suitable features for the design of enterprise is identified. Given the lack of application of analogy in real-world design of enterprise, the research question for PS phase has been set as "What is a possible form of integration of analogical thinking into the creative design; and, for the purpose of applying analogical thinking in enterprise design, what evidence could demonstrate the existence of analogy in the enterprise context?"

This research question is explored primarily in Chapter 7, with the assistance of the understanding of creative and design process reviewed in Chapters 2 and 7, respectively. The design of enterprise, adopted as a chosen field of design application, is meant to involve the establishment and development of a commercial enterprise (see Section 8.1).

With the target of generating new findings, PS phase of this research is formed by two parts of studies: 1) The identification of analogy through analyses of existing enterprises and 2) A proposal to form a model in theory for creative design of enterprise, where analogical thinking is embedded. Both parts involve different research activities and methods. The combination of both phases undertakes a comprehensive PS phase assisted by review, with the assistance from existing literature and knowledge.

a. Identification of analogy through analyses of existing enterprises.

The study is conducted by analysing the existence of analogy in the development of enterprises of variable sizes, including large corporations and Small and Medium Enterprises (SME). This is done by identifying the existence of analogy in business leaders' public communication activities, through analyses of their public speeches' recordings and transcripts. Similar data is rarely available for start-up companies, so semi-structured interviews are conducted with a selection of 16 SMEs featuring start-up companies as the majority. The design of interview questions is around three key topics consisting of market requirements/gaps, technology and business development, all of which would require prioritised focus from a typical technology company. The consistent identification of analogy from the public speeches and interviews indicate that analogy exists in enterprise settings, and potentially are of value to the development of enterprise.

b. Proposal of an analogy-empowered creative design process

The identification of analogy's value in the development of enterprise, combined with the understanding of design process and creativity, leads to the idea of proposing a creative design process empowered by analogical thinking. The proposal is based on the evidence from understandings of creativity, analogy and design process, and is also supported by findings on analogy's value in the engineering design project introduced in DS-I phase in Chapter 6. The conceptualisation of interrelations between creativity, design and analogy have also contributed to the proposal, with creativity and imagination involved.

The elaboration and realisation of the proposal require further research on the integration of the analogy-empowered creative design process into a canvas for the design of sustainable enterprise. Evaluation is undertaken not as a separate step but throughout the whole of PS phase, where triangulation is formed by evidence from literature review, consistent existence of analogy in enterprise setting, and indication from the interview feedback. It is worth nothing the findings from DS-I phase are not utilised as fully verified evidence to avoid overgeneralisation, but the consistency in these findings should indicate reasonable validity for the proposal. Application Evaluation in greater details are undertaken in DS-II phase in Chapter 8.

4.2.4. Research methods in DS-II phase

The DS-II phase focuses on the initial evaluation of the design support developed by the PS phase, which is presented in the form of an analogy-empowered creative design process for enterprise. The evaluation of such a research outcome is difficult because the process suggests an innovative way to work towards the development of a new enterprise, and intangible features are involved in the application of the process such as human-centred elements and divergent-convergent thinking. Social research approaches are suitable to be applied for the evaluation because they evaluate organised social behaviours and the design of enterprise relates to these behaviours (Blessing and Chakrabarti, 2009).

An evaluation approach embedded with qualitative, naturalistic and formative elements has been considered suitable for studies such as this one, of which the application is interested in improving design effectiveness, integrating with enhanced creativity, and increasing the completeness of design outcome (Patton, 1990). A case study is undertaken focusing on the identification of key elements of a start-up company. The study deploys the framework illustrated in Figure 4.5, with a detailed plan and implementation described in Chapter 8.

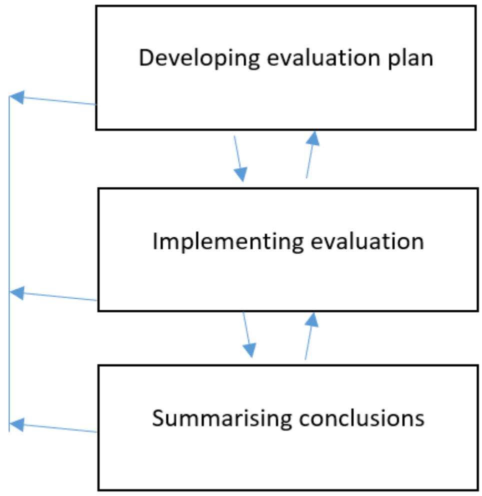


Figure 4.5. Key evaluation activities in DS-II phase

The study in Chapter 8 attempts to conduct an Application Evaluation of the design support from PS phase, in order to find answer to the research question "How to apply analogical thinking so that it can benefit a real-world enterprise design project?" Intended for Action Research, the researcher applies analogical thinking as problem owner in the establishment process of a start-up company, where key phases including the identification of market requirements, technology improvement and business development are identified and chosen to apply analogical thinking. The evaluation is also qualitatively realised by the recognition from expert feedback in the business field.

4.3. Discussion on research ethics, methodologies, methods and quality

4.3.1. On research ethics

Research ethics have been treated with utmost importance throughout this study to ensure the moral principles relating to the research are always acknowledged and fulfilled. This study involves rich investigation in the realm of enterprise, particularly in entrepreneurship and start-up business, therefore, the safeguarding of the intellectual property of businesses involved is most important and always observed. No confidential information on specific technology or business strategy has been disclosed or implied in the case studies. All case studies are carried out with the clear consent from the participants (engineering design and enterprise projects, workshops and interviews) and sponsor (engineering design project). The only exception is the analyses of public speeches from chosen business leaders reported in Chapter 7, where all data are publicly available and openly accessible.

In addition to the protection of intellectual property, all efforts are made to safeguard the confidentiality and anonymity of the participants of the study. For instance, the reporting of data from the interviews with enterprises in Chapter 7 are treated in an anonymous fashion, so that it would be impossible to identify specific business and personnel. These measures are in place to protect both personal privacy and business confidentiality. The extra information that is irrelevant to the study scope is omitted from the reporting, such as product formula and specific business strategies regarding the enterprise design project reported in Chapter 8.

4.3.2. On research methodologies

As presented in detail in earlier sections of this chapter, DRM has been selected as the overall research methodology for this study due to its systematic structure leading to comprehensiveness including literature clarification, empirical analyses, and theoretical assumption. In addition, the emphasis on evaluation for prescriptive studies helps increase the research validity (Blessing and Chakrabarti, 2009). However, limitations exist in the theoretical development and practical application of DRM in design research as observed through the study. 1) The continuous development of DRM as a new methodology should occur and benefit from the approximately 10-year history of application and feedback, and potential improvement should be expected as the result of its application in design research as theoretical advance. Any update of the DRM would be capable of contributing to the ever-evolving topics and requirements of design research. 2) Despite DRM having a recommend structure consisting elements of Research Clarification, Descriptive Study and Prescriptive Study, more tailored guidance for applying DRM to specific research scenario is limited. Design research is a broad field often involving multi-disciplinaries and diversified requirements; design research projects with various criteria at early stages could benefit from more tailored and specific guidance for applying research methodology and methods. DRM could contribute to a greater extent to design research with improved applicability while maintaining flexibility and adaptability.

Alternative research methodologies are available and potentially applicable, although deemed less suitable for this study. One such alternative methodology identified is Design Science Research Methodology (DSRM), which includes six phases as 1) Problem identification & motivation; 2) Objectives definition for solution; 3) Design & development; 4) Demonstration; 5) Evaluation; 6) Communication (Peffers et al., 2007). The DSRM allows for iterating back to redefining objectives and improving the research design, from phases of evaluation and communication for improved performance. However, the linear structure of DSRM lacks the combination elements of descriptive study and prescriptive study, which are essential to develop and evaluate analogical thinking method in this study. In addition, the DSRM is expected to be more effective and suitable for design research with new artefacts or process as aims in the realm of Information Systems (Peffers et al., 2007).

Another relevant and potentially applicable research methodology for this study has been identified as the Soft Design Science Methodology (SDSM), which includes eight key phases: 1) Understand specific problem; 2) Identify general requirements; 3) Explore general solution; 4) General evaluation in design thinking realm; 5) Achieve specific solution for design problem; 6) Specific evaluation in real world; 7) Finalise specific solution; 8) Conclusive evaluation (Baskerville et al., 2009). Inspired by the Soft Systems Methodology (SSM) (Checkland and Scholes, 1990), the SDSM provides a valuable attempt to integrate design research with systems thinking that searches for solution to real-world problems within the realm of system thinking field. In practice, SDSM and SSM are more suitable for specific application based problem-solving rather than for research-oriented application. Furthermore, the outcome from both of the subjectivist methodologies is likely to be improvement of the concerned product or organisation, compared to potential contribution of design theory of general value for this study as a whole. On balance the merits of SDSM and SSM are considered to be unsuitable as an overall research methodology. However, SSM is utilised as a guidance for the second descriptive study discoursed in Chapter 8, for its advantages towards organisation improvement through the reflection from system thinking to real-world problem solving.

4.3.3. On research methods

Qualitative and quantitative are the two prominent characteristics for describing research methods, data types, or the methods for data analysis. In the environment of design research, a qualitative approach explores the nature of phenomena with methods such as interviews and observations; a quantitative approach investigates the extent of phenomena with methods such as experiments and statistics-based surveys (Blessing and Chakrabarti, 2009). Qualitative research aims to gain understanding and explanation of behaviours and motivations for their reasons and processes, through interpretive analysis of typically small sample of textual data by methods such as interview and observation; while quantitative research aims to measure and quantify the degree of phenomena and behaviours, through objective analysis of typically large sample of statistical data by methods such as experiment and survey (Hennink et al., 2020). The most frequently adopted qualitative research methods include case study, focus group and field research, while survey and correlational study are identified as common quantitative research methods (Queirós et al., 2017).

Although qualitative and quantitative research methods function with merits due to their characteristics and focuses, there are inherent limitations to both. Implementation of qualitative research can be time-consuming (Choy, 2014). Ambiguities from data collection and analysis are recognisable; the relatively small sample of data resource determines that the findings are challenging to be generalised and extended to much wider populations for the same level of certainty (Ochieng, 2009). Quantitative research, on the other hand, could be comprised by lack of resources required for large-scale study, and description of human experience is challenging to achieve. Therefore, a combined and complimentary application of qualitative and quantitative research methods can be expected to reach more valid and effective outcomes (Choy, 2014, Queirós et al., 2017).

The understanding of strengths and weaknesses of qualitative and quantitative research methods leads to the application of mixed methods research (MMR) in this study. “Mixed methods research is the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the broad purposes of breadth and depth of understanding and corroboration” (Johnson et al., 2007, p. 123). The overall purpose of MMR is to strengthen the research outcome by achieving enhanced knowledge and validity as the result of multi-angle qualitative and quantitative approaches. Although careful design and implementation of MMR is essential, which could lead to intensive time and effort requirements (Schoonenboom and Johnson, 2017).

This study aims to apply qualitative driven MMR to address research purposes and questions. All MMR should have at least one point of integration for qualitative and quantitative elements (Schoonenboom and Johnson, 2017). For instance, in the case study on engineering design, points of such integration are expected to occur in the research method, data collection and data analysis, in compliance with the exploratory research question through a triangulation approach. In the evaluation phase of this study, a questionnaire is used to gather feedback from participants. Although it would be difficult for the chosen case studies to fit all purpose of research, and therefore the findings should not be overly generalised, case study as a useful method is capable of providing comprehensive yet detailed information that helps to disclose research insights (Queirós et al., 2017).

Mixed experience of utilisation of interviews as a research method has also be observed. For instance, as a part of the main prescriptive study 16 interviews indicated insightful and detailed information on the domain of entrepreneurship, with great flexibility in implementation. However, the resource to achieve the opportunity for interviews are significant, and the findings should not be overstated in validity without consistency from other complimentary approaches because of the sample size and potential bias.

4.3.4. On research quality

In addition to the measures on research methodology and methods to ensure validity and rigor of this study, further considerations are carried out on overall research quality including reduction of participant bias and coding bias in case studies. Participant biases commonly exist in case studies, especially when observations, interviewing, and experiments are involved (Yin, 2017). Participants' behaviour may respond positively, negatively or neutral to the confirmation of research hypotheses, with the influencing factors including personality, attitude towards the study, and participants' fore-knowledge about the hypotheses (Nichols and Maner, 2008). Measures are taken to minimise participants biases in the case studies. For instance, in the engineering design project no preference for certain creativity tools are indicated during creative ideation to reduce participant demand. The selection of technology entrepreneur companies endeavoured to include a wide variety of industries rather than limiting the targeted participants into the same industry. Furthermore, the participants were not informed of the research purpose on analogical thinking until the interviews have been completed; therefore, no foreknowledge is expected to influence the insights as the result of hypothesis guessing.

Coding bias has also been minimised during data analysis in this study. For instance, with the appropriate consent from the interview participants, tape recording has been adopted in addition to notetaking. This data then is able to be scrutinised for accuracy and consistency. Detailed mitigation measures are discussed in the case study sections. Limitations caused by research bias should be recognised despite all the efforts for achieving high research quality.

4.4. Conclusion

DRM is adopted in this research as a comprehensive and systematic research methodology. This research, as a typical structured study, chooses to follow DRM from Research Clarification phase, although DRM could be adopted from any phase within. DRM provides the research with a clear and well-structured guidance while no limitation has been identified during its application. The iteration of DS-II phase is possible, and this study conducted the DS-II evaluations of the design support suggested by PS phase through a real-world application. Empirical studies are involved in both DS-I and DS-II phases but with different objectives. DS-I aims to acquire in-depth understandings of current situation with possible suggestions, while DS-II aims for the evaluation of the design support developed. The evaluation is important as it ensures the positive evolvement of any outcome of design research. There are three principles to follow, to help manage the focus of study:

- Referring to the literature review at each phase of DRM to ensure the validity of evidence on which the methodology depends.
- Undertaking a comprehensive study for DS-I, PS and DS-II phases, unless the constraints of resources forbid doing so.
- Undertake a sufficient level of evaluation at DS-I, PS and DS-II phases to ensure that the understandings and new findings are verified.

To help conclude the strategy and organisation of this study, a Question-Method Matrix analysis is conducted to further refine the research questions and select suitable research methods as shown in Table 4.2 (Blessing and Chakrabarti, 2009).

	Strategic literature Review		Recording of sketch data in idea generation		Multiple choice questionn aires		Semi-structured interviews		Archival files analysis		Action Research	
	On creativity analogy & design		Conceptual ideation		Feedback from case study		Selected enterprises		Work-shop notes; videos of speeches		Follow the Soft Systems Method	
Research Question 1	✓		✓		✓				✓			
	RR		RR	PP	R	P			R	P		
Research Question 2	✓						✓		✓			
	R						R	P	R	PP		
	✓										✓✓	

Research Question 3	R										RR	

Table 4.2. Question-Method Matrix Analysis for this study

For the analysis purpose of the potential research methods for each research question, one tick (✓) indicates the utilisation of the method in the study for answers to the relevant research question; while two ticks (✓✓) indicate primary adoption of the method. The degree of effort by the Researcher (R) and the Participant (P) is indicated under each method for each research question, where a differentiation is made between a small effort (R/P) and a large effort (RR/PP).

Chapter 5. Analogical Creative Process

This Chapter, positioned as an initial Prescriptive Study, endeavours to propose a systematic method to apply analogical thinking in the context of creative design. This proposed method is based on the understanding of creativity and analogy from the literature review, and inspired by the observation of Biomimetics in research with the subject of biology as the source domain. Attempts are identified to mapping analogically from biology to design, however, such mappings are not derived from the fundamental cognitive theories of analogy therefore lack systematic elements. The Analogical Creative Process (ACP) proposed could be valuable in not only establishing analogical mappings, but also providing the theoretical basis for various of tools in future studies.

5.1. Analogy and analogical thinking in design

5.1.1. Design by analogy

Analogy exists in well-known stories as an inspirational stimulation for new ideas within design contexts. The use of analogy in design is popular in design and engineering consulting industry (Kalogerakis et al., 2010). The great civil engineer and inventor Isambard Kingdom Brunel used analogy in a number of his projects: "…immediately drew a sketch of (Isambard Kingdom) Brunel's bridge across the Tamar… and pointed out that in the body of an elephant nature had previously adopted the same means of sustaining a heavy weight…(Dawson, 2016, p.204) " "The roofs of the Bath and Bristol stations are of large span…The framing is an example of a peculiar from of construction, somewhat analogous to that adopted in the large shipbuilding sheds in the dockyards;" and "…plate girders, with continuous webs made of plates riveted together, and therefore analogous to the beams of cast iron which they almost entirely superseded" (Brunel, 2011, p.195). Product designer Mark Sanders developed an innovative folding bicycle aiming not for the smallest size when folded but as 'a stick with wheels at one end', with the assistance of analogical transferred from the folding functions of the Maclaren baby buggy (Roy, 1993). Sander's one- touch can opener aimed to change the image of a can opener from a "sharp metallic tool" to a smooth "egg-like form" (Sanders, 2019). The BMW Group transferred the use of joystick from the video game industry into the design of human-car interaction to create the iDrive interface in 2001, and successfully eliminated up to 200 controlling knobs and switches (Gassmann, 2008).

Within-domain analogy is sometimes referred to as near (surface) analogy, while between-domain analogy as far (structural) analogy (Dahl and Moreau, 2002). Near analogies are easier to identify than far analogies, as the within-domain context often offers attribute similarities while the between-domain contexts only discloses similarities in structural relationships between source and target domains (Gassmann, 2008). Analogy is found to be beneficial in identifying problems (mainly within domain), solving problems (both within and between domain) and explaining concepts (mainly between domain) in novel engineering design projects (Christensen and Schunn, 2007). Promotion of generation of distant analogies has been observed in assisting on forming a mind-set, which encourages relational analogical mapping in problem solving, although the reason for this phenomenon requires further study (Vendetti et al., 2014). A positive correlation was discovered between the amount of analogical thinking and the originality of proposed design. The increased likelihood of originality of product design is also caused by the percentage of distant analogies used. More analogies are generated when multi-base domains are encouraged to use compared to one base domain (Dahl and Moreau, 2002). However, in this study, the mean difference of originality is small in the research observation and no experiments are conducted on professional designers to maintain the focus of study. Analogical distance is found to be positively relevant to the novelty and originality while negatively associated with project duration. While analogies from local general knowledge source are efficient in design ideation, those derived by designers from existing technological solutions or functions tend to be more effective (Kalogerakis et al., 2010).

As illustrated in the cognitive process of analogy, the establishment of analogical mapping between the source and target domains is key to benefitting design by analogy. Analogical approach plays a key part in problem definition and conceptual design phases, as suggested by a systematic literature review to identify methods for problem-driven application of biologically inspired design targeting multi-functional problems (Svendsen and Lenau, 2019). In order to enhance the effectiveness of application search for solution-driven biologically inspired design, a process is proposed, starting with open search for characteristic analysis, and refined with the search for applications with constraints applied, but more applicable studies are necessary to provide further evidence of testing (Lenau, 2019).

Both experienced and novice designers can benefit from using analogy with guidance in design projects. The deliberate use of analogy achieves better results (Casakin and Goldschmidt, 2000, Ball et al., 2004, Casakin, 2004). It has been established that application of visual analogy improves the design quality, and such improvement is more significant for novice designers (Casakin and Goldschmidt, 1999). Experts designers tend to use more analogies than novice designers in design; and expert designers tend to use schema-driving analogising (application of abstract experiential knowledge leads to more general design solutions) compared to case-driven analogising (an existing concrete example leads to solution to specific design problem); a reverse pattern is exhibited by novice designers (Ball et al., 2004). Expert designers identified and retrieved analogues from between-domain displays while novice designers were also capable of focusing on between-domain displays (Casakin, 2004). Expert designers tend to deploy analogy for problem identification, whilst novice designers focus more on the quality and appropriateness of analogy (Dinar et al., 2015). Similarly, it has be observed that more experienced designers tend to concentrate more on the overall completeness of design whereas less experienced designers tend to pay more attention on design functionality (Chai et al., 2015). These findings echo with the difference observed in cerebral activities between expert and novice experience designers using electroencephalography, although further evidence from neuroscience studies is required for clarification (Liang et al., 2019).

5.1.2. Analogy with Biology as source domain

Similar to the principle of TRIZ, BioTRIZ is based on the analyses of biological effect, and helps to derive technical solutions through analogical mapping from the biological world by categorising possible solutions concerning substance, structure, space, time, energy and information (Vincent et al., 2006). Both the lexical methods and BioTRIZ attempt to explore the biological effect in a systematic fashion to ensure that all the potential solutions can be mapped over to solve technical and design problems. However, in the absence of an effective guided approach, the best chance of success should still depend on the existing information provided by biologists, whose discoveries offer a comprehensive understanding of a given system of phenomenon in the biological world as analogues. For example, the in-depth analyses of a selection of micro-structures of plant surfaces provides a valuable source of domain information of the associated functions, which could lead to potential technological developments such as new materials. A few suggested connections between the plant surfaces and technologies are shown in Table 5.1. (Koch et al., 2009).

Plant	**Functions of surface**	**Possible technological development**
Lotus leaf	Self-cleaning	Self-cleaning materials/treatment
Water ferns	Superhydrophobic, air-retraining	Hydrophobic or hydrophilic materials/treatment
Many desert plants	Light reflecting	Light reflection materials/treatment
	Reducing water-loss	Water preservation solutions

Table 5.1. Examples of plant surface research leading to possible technologies

The interesting challenge in the design-by-analogy with biology as the source domain is how best to support analogical thinking in design processes. As analysed in the review of analogy, for instance professor Maiden's approach to tackle the challenge is two-fold: 1) discover and introduce analogies manually into design workshops and allow stakeholders to interpret the analogical domain elements in the creative process; 2) automatically retrieve analogical cases through advanced search tools. Both have been moderately effective. However, individual cognitive traits and differences have an important part to play; many people struggle to reason by analogical similarity, and the undirected nature of analogical reasoning can reduce its cost-effectiveness in constrained design work. Further exploration in the direction of developing a systematic analogical method that can be utilised regardless of the user's experience or background continues to emerge with value.

5.2. Knowledge gaps on analogy in creative design and relevant research questions

5.2.1. Knowledge gaps

The use of analogy in design has been extensively found in the design of products, particularly in the conceptual design phase where attempts are made to identify creative design ideas by mapping analogically from the source to target domain. For instance, a systematic method featuring design-by-analogy is reported to help designers identify analogies in conceptual design phase, while the analogies are extracted from databases of patents (Fu et al., 2015). Findings are reported that distant analogies do not necessarily lead to more novel generation of concepts, but instead contribute to an increased generation rate for concepts compared to ideation with absence of analogy (Chan and Schunn, 2015). This type of research typically focuses on intentional use of analogy by designers in conceptual design phase, and attempts to derive insights towards better acknowledgement of analogy's value.

Analogical thinking has been adopted in research to enhance creativity in design (Kryssanov et al., 2001). However, a more systematic approach for analogical thinking on the basis of the establishment of analogy has yet to be developed, to the author's knowledge. Such an approach should be versatile for different domains in design, including engineering design and the design of enterprise, as its form is irrelevant to application domains. Furthermore, the strategic literature review suggests that, compared to the rich studies on the impact of analogy distance in design, and the different patterns expert and novice designers behave when using analogy in design, few studies have explored the nature and prevalence of spontaneous analogising in design contexts. Limited amount of existing work on analogical processes in design is available (Ball et al., 2004). For instance, seven analogy categories (Form, Architecture, Surface, Material, Function, Process and System) are identified through review of bio-inspired design, and the diversity of analogy is utilised to provide insight on analogical transfer between biology and engineering domains. However, more suitable methods are needed to identify and apply promising analogies (Nagel et al., 2018). Therefore, it is worthwhile to investigate how to better apply analogical thinking in a creative design process within the context of design, including for instance engineering design and the design of enterprise.

More research on analogy in product design is necessary to fill the ad-hoc gaps in knowledge and to paint a fuller picture. For instance, it would be valuable to learn whether designers would use analogy in conceptual design ideation, either intentionally or non-intentionally, without the prior mention of analogy. The findings from this would not only disclose the acceptance of analogy by default, but they also illustrate the value of analogy's application without intention. Furthermore, previous studies have suggested analogy outperforms non-analogical baseline ideation (Bonnardel, 2000, Linsey et al., 2012). However, the design research should be able to benefit more from the comparable effectiveness of analogy in creative ideation from the existing creativity tools in design.

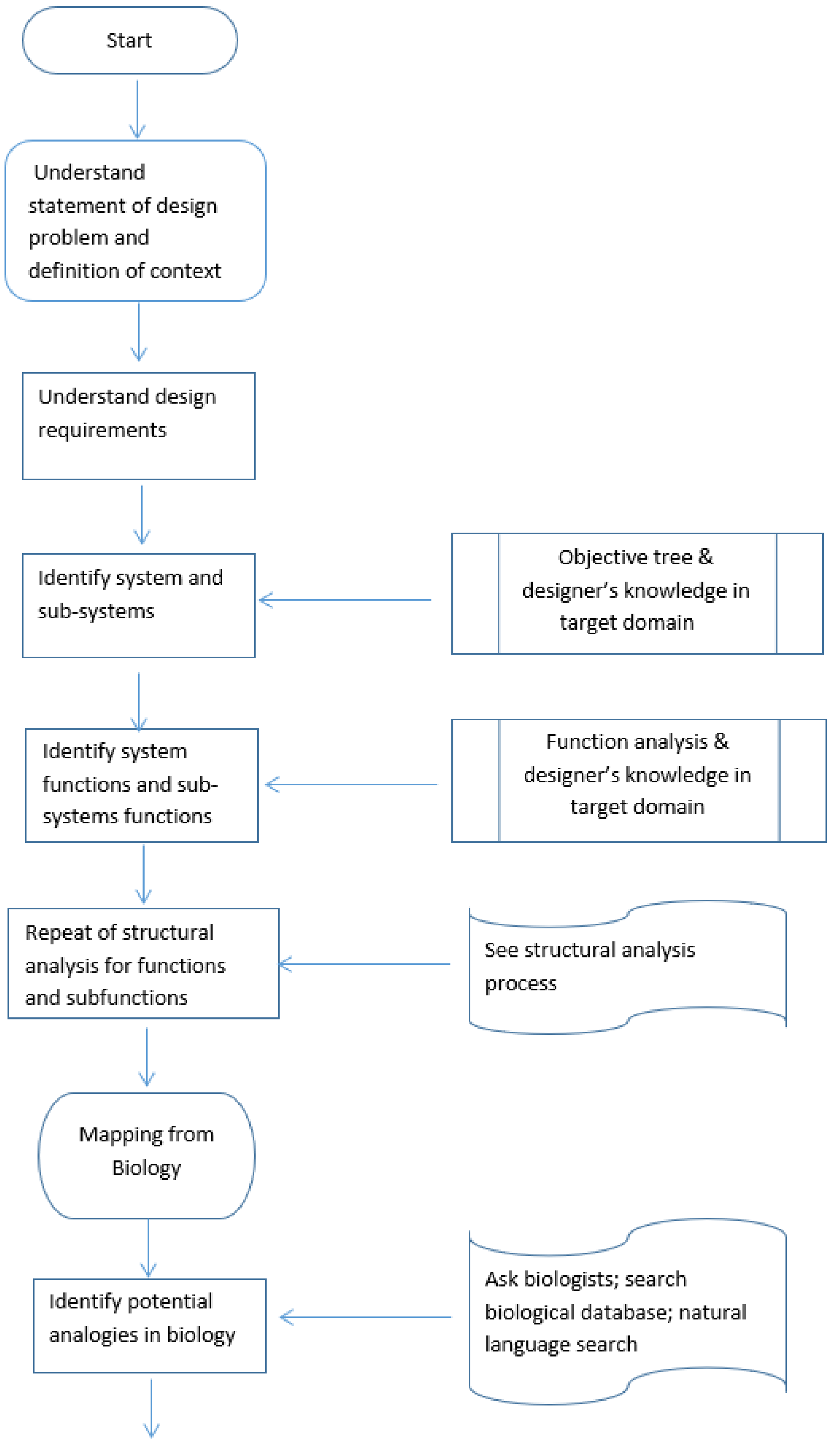
5.2.2. Research questions

To fulfil the knowledge gaps identified in the use of analogy in project design, several key research questions have arisen (see Section 4.2 for details). 1) How effective is analogical thinking in the conceptual design ideation of a real-world engineering design project? 2) What is a possible form of integration of analogical thinking into the creative design, and, for the purpose of application of analogical thinking in enterprise design, what evidence could demonstrate the existence of analogy in the enterprise context? 3) How to apply analogical thinking so that it can benefit a real-world enterprise design project?

These research questions focus on support for creative design and will be explored further in subsequent chapters for any possible answers. Further elaboration can be found on use of analogy in the design of enterprise, where little reports seem available currently. The absence of findings for analogy in enterprise design indicates huge needs for investigation with the potentials research outcomes expected. Such research activities are reported in the studies on analogy in the design of enterprise in Chapter 7 and 8.

5.3. The proposal of Analogical Creative Process model (ACP)

The Analogical Creative Process (ACP) is a guided process to apply analogical thinking for design projects. It is derived from the understanding of cognitive process of analogy and the theories for analogy's establishment. A version of ACP is illustrated in Diagram 5.1 with the biological world as the source domain. ACP is developed with two key elements: analogical mapping and step-by-step form. Analogical mappings between the source domain and target domain are essential to stimulate new connections and ideas, while the step-by-step form of ACP helps users follow the analogical thinking process without an in-depth understanding of the theories of establishment of analogy. ACP is not meant to be a rigid process but offers adaptability to the design task and user's experiences of analogical thinking. An application of ACP is illustrated in the engineering design project in Chapter 6. An analogy-empowered creative design process for enterprise, which is essentially powered by ACP as element of analogical thinking, is proposed in Chapter 7 and evaluated in Chapter 8.


Start
Understand statement of design problem and definition of context
Understand design requirements
Identify system and sub-systems
Objective tree & designer's knowledge in target domain
Identify system functions and sub-systems functions
Function analysis & designer's knowledge in target domain
Repeat of structural analysis for functions and subfunctions
See structural analysis process
Mapping from Biology
Identify potential analogies in biology
Ask biologists; search biological database; natural language search

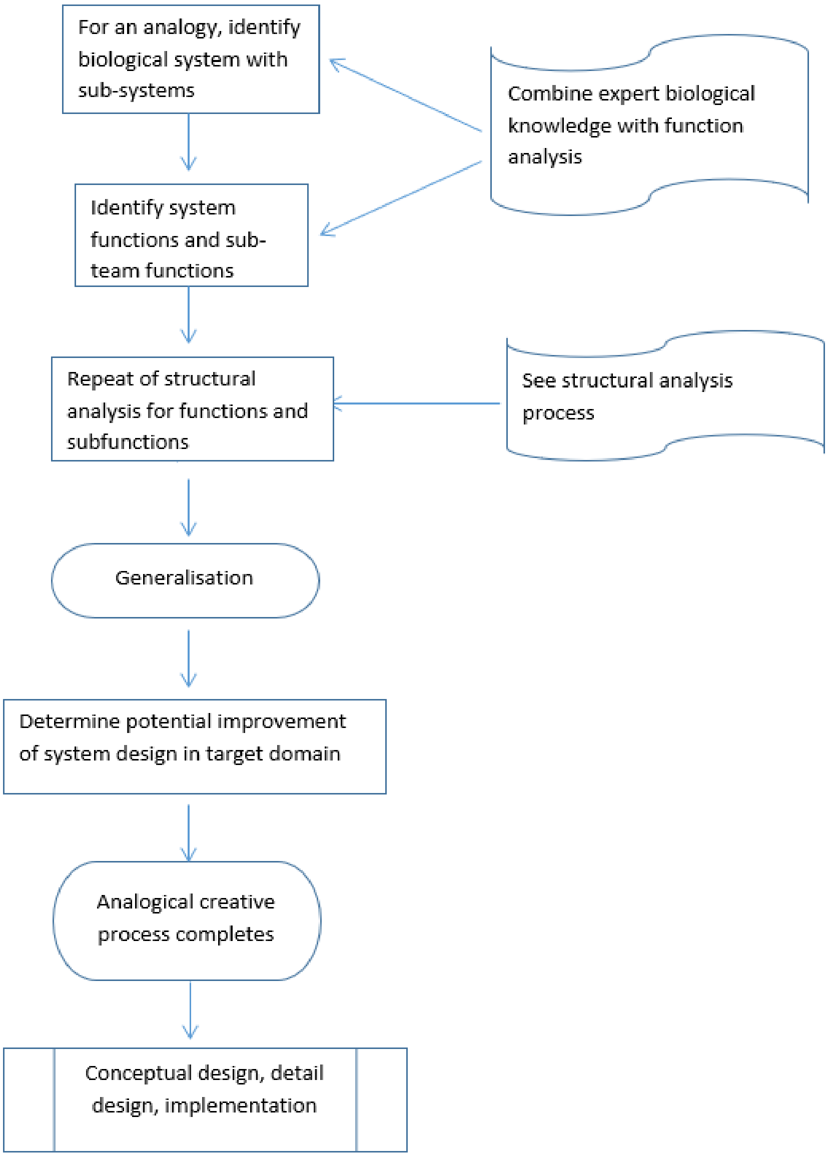


Diagram 5.1. Illustration of ACP with biological world as source domain

ACP seeks to be capable of assisting both designers who are familiar with analogical thinking and those without knowledge or previous experience with analogy. Designers who are familiar with analogical thinking can use ACP as a reference for key process, while those not familiar are able to refer to the step-by-step guidance for systematic application of analogical thinking in creative design. The process of analysis of domains is illustrated in Diagram 5.2.

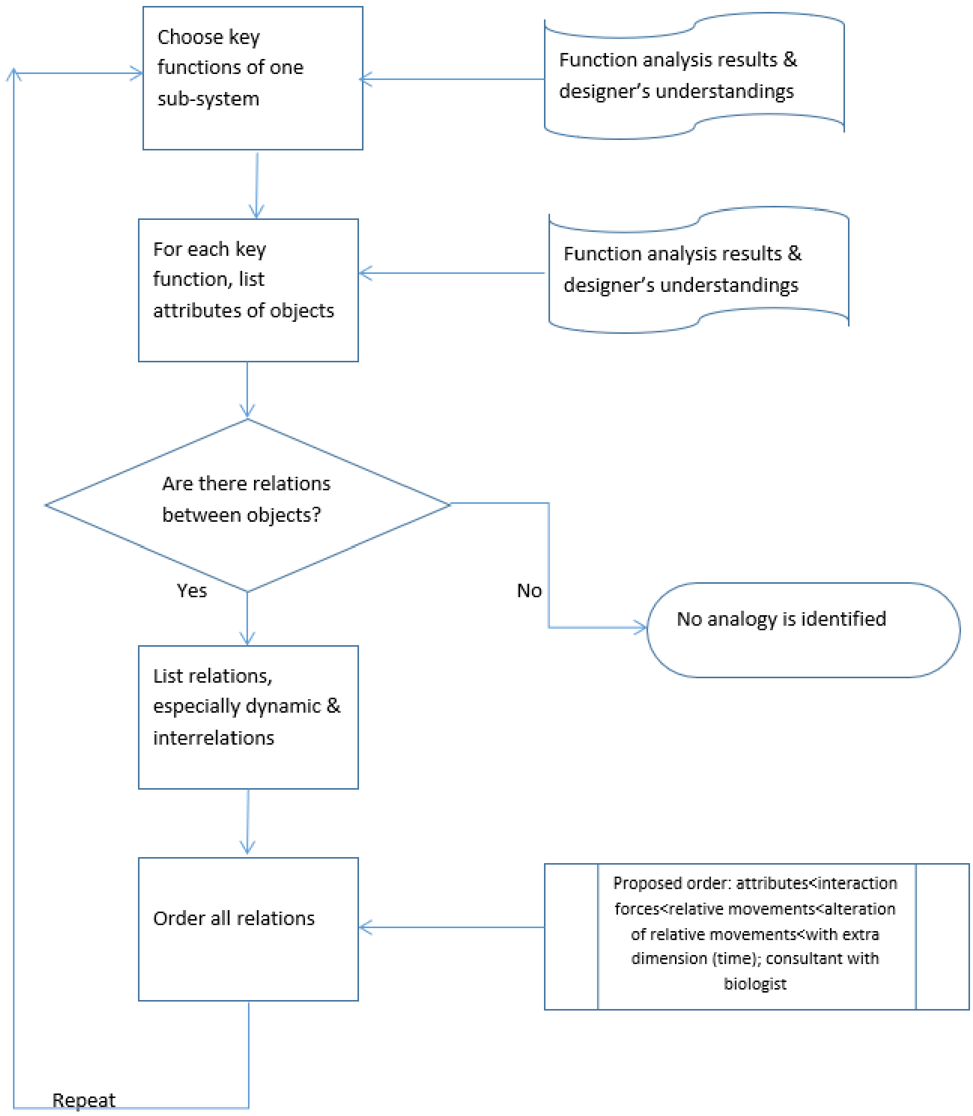


Diagram 5.2. Process of structural analysis for domains

ACP provides guidance for an analogical thinking process derived from the review of creativity and analogy, presented in the framework of a flow diagram. Although currently in early stage and form, ACP has the potential to be positioned as a theoretical method featuring analogical thinking in design, and holds value in deriving various of tools for creative design. For instance, software or mobile applications could benefit from ACP in following its systematic structure underneath the user interface to provide analogical solutions. The value of ACP is inherited from its development where the cognitive process of analogical mapping is followed. Its key essence is to rigorously preserve all phases of the cognitive process of analogical thinking, and to provide the designer with clear step-by-step suggestions. However, it is not necessary to focus to every individual step within the ACP for all design projects. The judgement is that of designer's.

ACP is flexible and adaptable to the chosen source domain and the level of understanding of it. For instance, the key phases of the ACP illustrated as below focuses primarily on engineering design with biological world as the source domain (see Diagram 5.1). A more detailed version is illustrated in Appendix 3. Other adaptive versions of ACP would also be suitable for the design of enterprise with diversified choices of the source domains but analogical thinking as essence.

5.4. Conclusions

With recognition of the flexibility of DRM and its heuristic intention in guiding the research structure, an Initial Prescriptive Study (IPS) has been implemented to represent the development of ACP from the theoretical findings of RC phase. The IPS endeavours to not only further highlight the desired value of ACP as the proposed support in analogical thinking developed from relevant review of creativity and analogy, but also define the clarified research scope for analogical thinking in engineering design and enterprise. The ACP developed in the Initial PS would be applied and evaluated in the following empirical studies reported, before being concluded as part of the updated impact model.

The application of analogical thinking enhances creativity thus would lead to more innovative design outcome; however, the existing evidence lacks presentation of analogical thinking as a generic systematic process or method, which is capable of providing users with applicability and usefulness of analogical thinking, as well as the application value of such method in real-world design situations.

Based on the analytical review of literature on creativity and analogy, especially the value of analogical thinking in design, the absence of an approach for systematic utilisation of analogy in design has been identified. This Chapter continues to propose a systematic method as guidance for application of analogical thinking in design in the form of a step-by-step ACP. Compared to the existing approaches of using analogy in design, ACP as a method offers more explicit guidance for the users and requires less training in analogical thinking. ACP is utilised in the ideation for conceptual design of an engineering design project in Chapter 6 where its value is to be analysed and evaluated. A complete flowchart of steps of biology-inspired analogical thinking in design has been proposed as a result, and the value of such process is to be tested by utilisation in case studies to follow.

Chapter 6. Application of analogical thinking in an engineering design project

This chapter explores the effectiveness of analogical thinking in the context of a real-world engineering design project. In the conceptual design phase for this project, a comparison of non-analogical and analogical creativity tools is conducted to realise the output difference in idea generation, where ACP is highlighted as a tool of analogical thinking. In order to enhance the study's outcome, a research method of triangulation is adopted utilising findings from the existing literature and practical workshops, the ideation results of this case study, and from feedback evaluation for analogical thinking.

6.1. Engineering design project background and research questions

6.1.1. Engineering design project background

With the aim of applying creative design research into real-world design project, a group of PhD students accepted the assignment to further develop the design concept. The concept involves development of a pre-production prototype of key modules for a water desalination unit powered uniquely by solar energy. The design team was informed that this unit would aim to ease the water-stressed issue of users from all socio-economic strata, especially those with very limited disposal incomes.

The design task had specific primary requirements including:

a. A Minimum daily production of 15 litres drinkable water
b. Maximised robustness, reliability and longevity
c. Controlled production cost of USD $425 per unit (as at 2016)

There were also secondary requirements:

d. Controlled weight (75 kg +/-10 kg) and size (approximately 2 m*2 m)
e. Ease of operation
f. An appeal for customers

The design approach included four phases following a typical product design task: 1) Descriptive study; 2) Conceptual design; 3) Crude Prototype development; 4)

Prototype refinement and testing. The key technical parameters of this design project and the correlations between parameters involved in a membrane testing rig are briefly discussed in Table 6.1.

Influence of design parameters on permeate flux (fresh water output), ordered by significance	
Td=T(hot)-T(cold) Temperature difference between hot water and cold water	Highly significant effect on fresh water output If Td increases↑, then output increases↑ So make the temperature difference as big as possible
Air gap width (distance between membrane and condensation plate)	Highly significant If width ↑, then output ↓ For 7 mm, 5 mm, 3 mm, 2.3 mm, 2 mm, 1 mm: 1 mm would be the best
Flow rate	Significant If flow rate increases↑, then output increases↑ Flow rate=1 L/min – 5 L/min
Pore size of membrane	Has a small effect 0.45 µm can get more output than 0.22µm. 0.45 µm is better.
Feed concentration	Little effect If the feed water concentration↑, then the output↓
Condenser plate	Brass
Example Reference	Normally, if $T_d(T_{hot}-T_{cold})=20^oC$, flow rate is 3 L/min, Air gap width is 3 mm, The permeate flux (fresh water output) would be: 11-14 kg/m^2h

Table 6.1. Key technical parameters and correlations

6.1.2. Case study objectives and research questions

In addition to meeting the engineering design requirements, this project is also treated as a research case study, which provides a real-world scenario to test the usefulness of analogical thinking in design ideation, and to thoroughly compare typical non-analogical creativity tools and analogical ideation tools. A formal consent to report and publish this study for academic purposes with research ethics has been obtained from the company to which the product belongs (See Appendix 5). The key design phase to apply this research for is the conceptual design phase, as conceptual design generally consists of the richest activity of creative idea generation. Furthermore, as the design team will have accepted the data found through the investigation on technical specifications and will have agreed on the primary and secondary design objectives, it would be an entry into the conceptual design phase of controlled ideation where the team's understanding of conditions is kept as similar as possible. This would in theory benefit the effectiveness and impartiality of the research.

This product concept proposes significant technical challenges for design. The core challenge is to solve the contradiction between limited energy supply (solely by solar absorber with restricted dimensions) and a high yield of drinking water production. The inevitable heat loss within the heat transfer processes in reality will cause further challenges, while the primary and secondary design requirements, such as cost, robustness, and weight etc., are expected to limit feasible solutions even further.

The team carried out research into background data and numerical calculations. As a result, it was agreed that the core technical approach for the most achievable product design solution would be to utilise a membrane to produce drinking water through a predominantly physical process. This development refines the problem-finding and converts the key product design task into how to design a membrane testing rig that fulfils all core technical requirements.

Since the key proposed findings from this research would be the usefulness of analogical thinking in a typical ideation setting, the key findings from this case study endeavours to answer the following research questions:

1. Can analogy bring extra value to ideation in the conceptual design of this engineering design project, compared to scenarios where only non-analogical creativity tools are applied?
2. What is the participating thinkers' feedback on application of analogical thinking and non-analogical thinking?

In order to conduct the case study involving analogical ideation while also progressing the conceptual design phase, a series of facilitated creative ideation sessions were held and all five team members participated. Due to commercial confidentiality, only the design team members were allowed to participate in the ideation sessions. The series of ideation workshops aimed to find answers to the above research questions through the most suitable methodology. A consent form (see Appendix 4) was signed by all participants to ensure that all the data can be used and published for research purposes.

6.2. Chapter methodology

For the full engineering design process, it was agreed by the team that a design process from fact finding to embodiment design and detail design would be conducted according to the client's requirements. The illustration of research methodology has been introduced in *4.2.2. Research methods and key activities in DS-I phase* in Chapter 4. To summarise, Mixed Methods Research (MMR) is adopted to combine elements of qualitative and quantitative methods, and the findings are verified by the method of triangulation, which is formulated by the consistency of data derived from different resources including literature review, the results of the empirical study and the feedback of the participants.

6.3. Execution of ideation

6.3.1. Structure of ideation

The outline of the ideation workshops was designed in such a pattern that all ideation tools, be it analogical or non-analogical, can be exploited to expected effectiveness, subject to the given same design project and similar constraints such as amount of time, participants' skills and experiences etc. Brainwriting and SCAMMPERR were chosen to be applied in the first two workshops because they are both effective creativity tools for idea generation (Coskun, 2005, Heslin, 2009, Melodi, 2016). To achieve this aim, tailored arrangements for the use of each tool was applied. For Brainwriting, evidence has shown that more ideas are achievable if the facilitator also participates in ideation, and that elaboration on initial ideas can lead to further improvements (Berry, 2012). Therefore, five rounds of ideation by brainwriting which encourage iterative elaboration were undertaken including the facilitator as one of the participants. The outline structure of ideation sessions is illustrated in Table 6.2.

Ideation type	**Creativity tools**	**Pattern**	**Facilitation during ideation**	**Total Ideation Time (min)**
Non-analogical	Brainwriting	5rounds*5 thinkers	Yes	75
	SCAMMPERR	1 round *5 thinkers	Yes	60
Analogical thinking	General analogy	1 individual session each for 4 thinkers	Yes	40
	Analogical Creative Process	1 Individual session each for 4 thinkers	Yes	40

Table 6.2. Outline of Ideation sessions with four creativity tools

The sequence of ideation with general analogy first endeavours to minimise the impact of introducing Analogical Creative Process otherwise, as it could lead to generation of biased data by general analogy once ACP is applied firstly. As ACP is new to the thinkers, a brief key training session was carried out before ideation with it. The training aims to familiarise the group with the procedure of ACP and its reasoning, which focuses more on the mapping of functions rather than attributes. It is worth noting that all four sessions are allocated at different dates with at least two days apart to minimise the influence from one another. Moreover, extra time is allowed for each ideation session to accommodate the needs for training, Q&A and breaks.

6.3.2. Brainwriting

Brainwriting was selected as the creativity tool for this first ideation session in contrast to the more widely-known brainstorming (see Section 2.3.1). In Brainwriting, participants are requested to write their own ideas down on paper and exchange them, where improvements of existing ideas are then encouraged. The simultaneously processing and improving of ideas eliminates productivity-blocking barrier of brainstorming (Geschka, 1975). In this study an extra round of ideation has be produced with the facilitator participating each ideation session. A representative data sheet with ideas recorded is illustrated in Figure 6.1. All representative date sheets illustrated are chosen to read with ease.

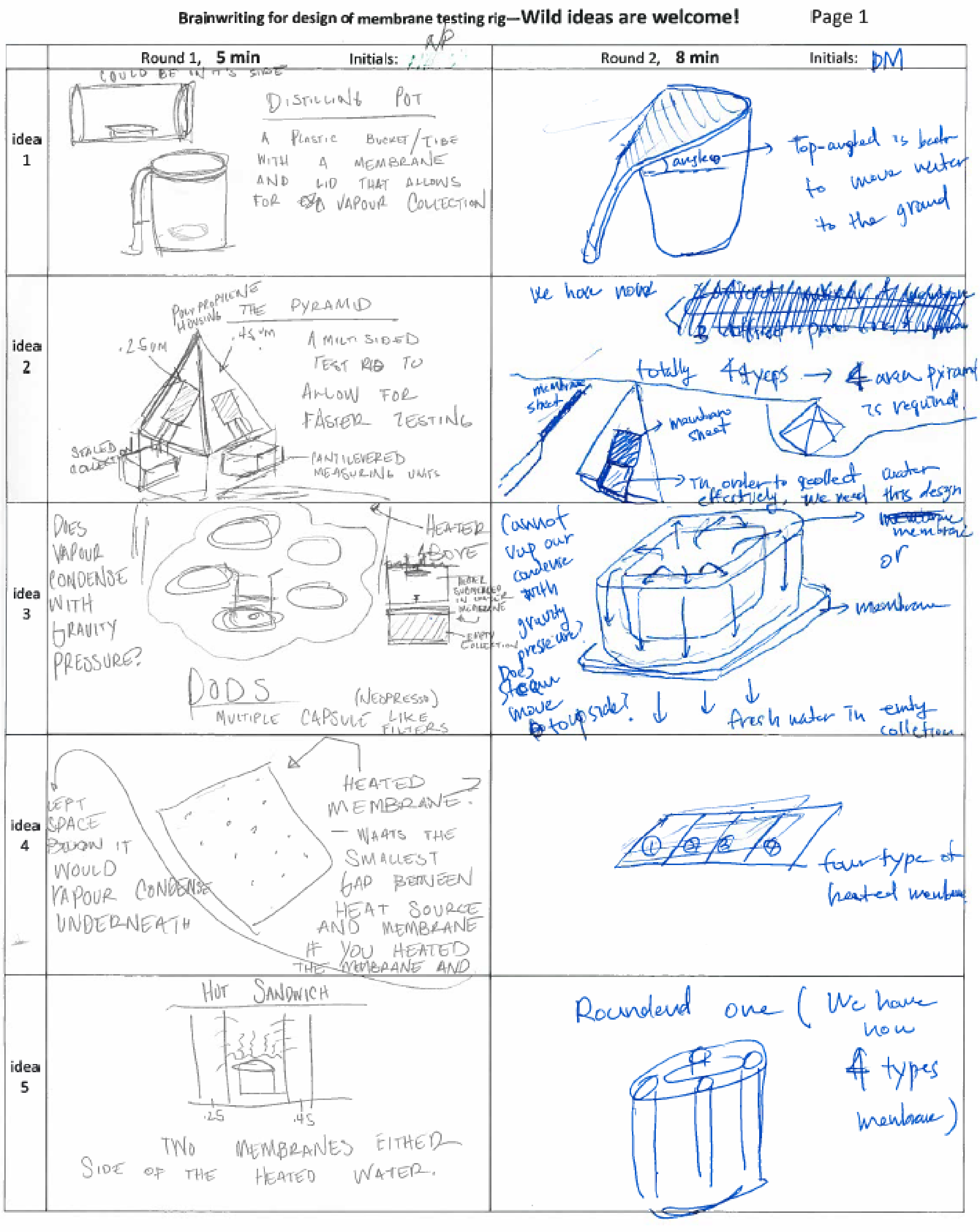


Figure 6.1. A representative data sheet from brainwriting

Table 6.3 illustrates the iterative structure of the ideation session using brainwriting. The concept and process of brainwriting are introduced in a brief training and Q&A session. Five thinkers are then represented as A, B, C, D and E and each thinker is given one sheet of "blank canvas" to record generated ideas on by texts, drawings or combinations of both. Five arounds of 15-minute ideation sessions are carried out. At the first round, each thinker is encouraged to generate five ideas and record them down. In the following rounds, all thinkers pass their canvases to the next thinker on their right-hand side, where five new ideas are generated based on the existing ones on the canvases. As the result of five rounds of ideation, 125 ideas and elaborations are successfully recorded. For instance, A_{23} stands for the third idea thinker A generated at the second ideation round.

Brainwriting for design of membrane testing rig

	Canvas 1 **15 min**	Canvas 2 **15 min**	Canvas 3 **15 min**	Canvas 4 **15 min**	Canvas 5 **15 min**
idea 1	$A_{11}/B_{21}/C_{31}/D_{41}/E_{51}$	$B_{11}/C_{21}/D_{31}/E_{41}/A_{51}$	$C_{11}/D_{21}/E_{31}/A_{41}/B_{51}$	$D_{11}/E_{21}/A_{31}/B_{41}/C_{51}$	$E_{11}/A_{21}/B_{31}/C_{41}/D_{51}$
idea 2	$A_{12}/B_{22}/C_{32}/D_{42}/E_{52}$	$B_{12}/C_{22}/D_{32}/E_{42}/A_{52}$	$C_{12}/D_{22}/E_{32}/A_{42}/B_{52}$	$D_{12}/E_{22}/A_{32}/B_{42}/C_{52}$	$E_{12}/A_{22}/B_{32}/C_{42}/D_{52}$
idea 3	$A_{13}/B_{23}/C_{33}/D_{43}/E_{53}$	$B_{13}/C_{23}/D_{33}/E_{43}/A_{53}$	$C_{13}/D_{23}/E_{33}/A_{43}/B_{53}$	$D_{13}/E_{23}/A_{33}/B_{43}/C_{53}$	$E_{13}/A_{23}/B_{33}/C_{43}/D_{53}$
idea 4	$A_{14}/B_{24}/C_{34}/D_{44}/E_{54}$	$B_{14}/C_{24}/D_{34}/E_{44}/A_{54}$	$C_{14}/D_{24}/E_{34}/A_{44}/B_{54}$	$D_{14}/E_{24}/A_{34}/B_{44}/C_{54}$	$E_{14}/A_{24}/B_{34}/C_{44}/D_{54}$
idea 5	$A_{15}/B_{25}/C_{35}/D_{45}/E_{55}$	$B_{15}/C_{25}/D_{35}/E_{45}/A_{55}$	$C_{15}/D_{25}/E_{35}/A_{45}/B_{55}$	$D_{15}/E_{25}/A_{35}/B_{45}/C_{55}$	$E_{15}/A_{25}/B_{35}/C_{45}/D_{55}$

Table 6.3. Illustration of brainwriting canvas for design of membrane testing rig

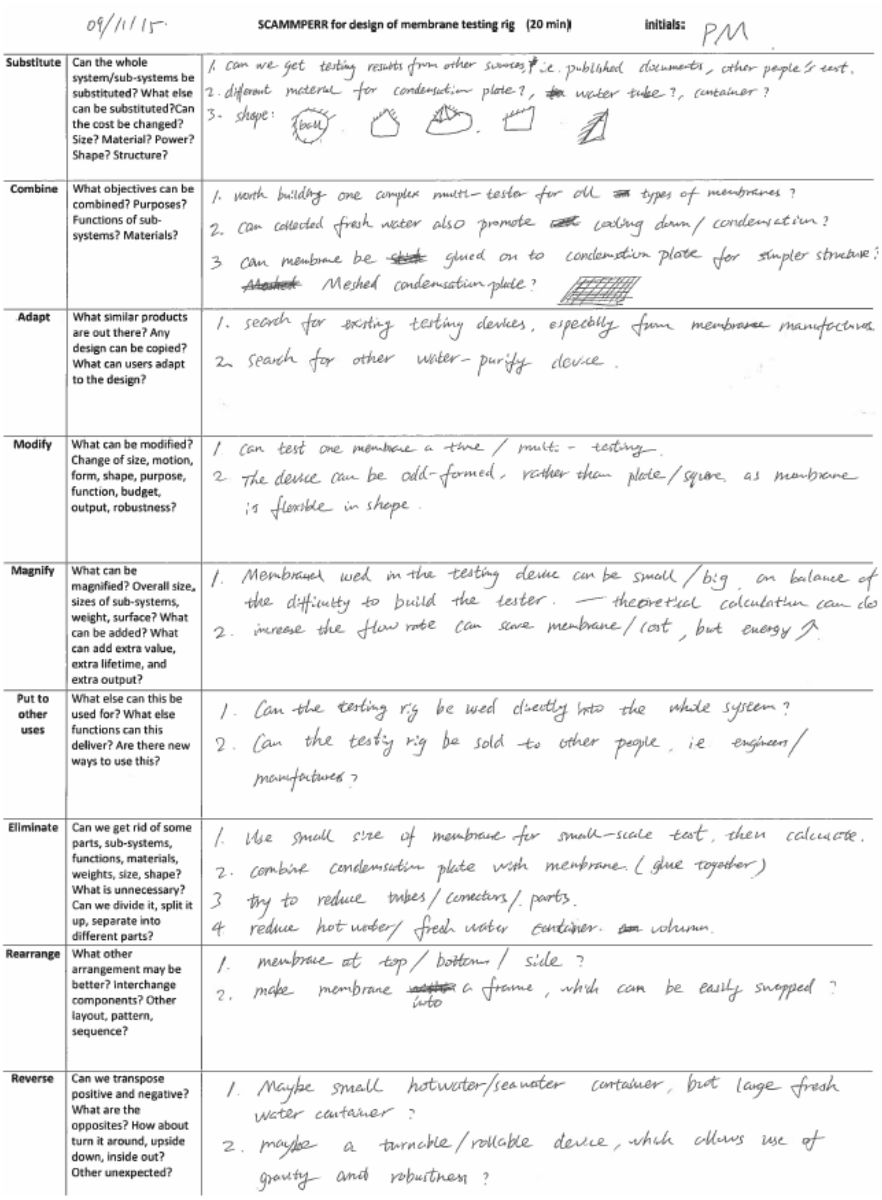
6.3.3. SCAMMPERR

SCAMPER is an acronym for Substitute, Combine, Adapt, Modify, Put to another use, Eliminate and Reverse; SCAMMPERR expands the list with another M for Magnify and another R for Rearrangement. SCAMPER works as a divergent thinking tool which offers a systematic approach by providing thinking directions. The effectiveness of SCAMPER has been widely reported since Eberle first suggested and used it (Eberle, 1972, Melodi, 2016, Glenn, 1997). In this study, thinkers are expected to utilise SCAMMPERR to elaborate on existing basic design concept of membrane testing rig and generate new design solutions. As shown in Table 6.4, for each suggested thinking direction, more detailed guidance is provided to inspire thinkers. These guidance work as part of facilitation and help towards ideation in restricted time.

SCAMMPERR	Guidance
Substitute	Can the whole system/sub-systems be substituted? What else can be substituted? Can the cost be changed? Size?
Combine	What objectives can be combined? Purposes? Functions of sub-systems? Materials?
Adapt	What similar products are out there? Is there any design that can be copied? What can users adapt to the design?
Modify	What can be modified? Change of size, motion, form, shape, purpose, function, budget, output, robustness?
Magnify	What can be magnified? Overall size, sizes of sub-systems, weight, surface? What can be added? What can add extra value, extra lifetime, and extra output?
Put to another use	What else can this be used for? What other functions can this deliver? Are there new ways to use this?
Eliminate	Can we get rid of some parts, sub-systems, functions, materials, weights, size or shape? What is unnecessary? Can we divide it, split it up, separate into different parts?
Reverse	Can we transpose positive and negative? What are the opposites? How about turning it around, upside down, inside out? Other unexpected?
Rearrange	What other arrangements might be better? Interchange components? Any other layouts, patterns and sequences?

Table 6.4. Illustration of SCAMMPERR canvas for design of membrane testing rig

A representative data sheet with idea generated by SCAMMPERR is illustrated as Figure 6.2.



09/11/15. SCAMMPERR for design of membrane testing rig (20 min) initials: PM

Substitute	Can the whole system/sub-systems be substituted? What else can be substituted?Can the cost be changed? Size? Material? Power? Shape? Structure?	1. can we get testing results from other sources? i.e. published documents, other people's test. 2. different material for condensation plate?, water tube?, container? 3. shape: (ball)
Combine	What objectives can be combined? Purposes? Functions of sub-systems? Materials?	1. worth building one complex multi-tester for all types of membranes? 2. Can collected fresh water also promote cooling down / condensation? 3. can membrane be glued on to condensation plate for simpler structure? Meshed condensation plate?
Adapt	What similar products are out there? Any design can be copied? What can users adapt to the design?	1. search for existing testing devices, especially from membrane manufactures. 2. search for other water-purify device.
Modify	What can be modified? Change of size, motion, form, shape, purpose, function, budget, output, robustness?	1. can test one membrane a time / multi-testing. 2. The device can be odd-formed, rather than plate / square, as membrane is flexible in shape.
Magnify	What can be magnified? Overall size, sizes of sub-systems, weight, surface? What can be added? What can add extra value, extra lifetime, and extra output?	1. Membranes used in the testing device can be small / big, on balance of the difficulty to build the tester. — theoretical calculation can do 2. increase the flow rate can save membrane / cost, but energy ↗
Put to other uses	What else can this be used for? What else functions can this deliver? Are there new ways to use this?	1. Can the testing rig be used directly into the whole system? 2. Can the testing rig be sold to other people, i.e. engineers / manufacturers?
Eliminate	Can we get rid of some parts, sub-systems, functions, materials, weights, size, shape? What is unnecessary? Can we divide it, split it up, separate into different parts?	1. Use small size of membrane for small-scale test, then calculate. 2. combine condensation plate with membrane. (glue together) 3. try to reduce tubes / connectors / parts. 4. reduce hot water / fresh water container. volume.
Rearrange	What other arrangement may be better? Interchange components? Other layout, pattern, sequence?	1. membrane at top / bottom / side? 2. make membrane into a frame, which can be easily swapped?
Reverse	Can we transpose positive and negative? What are the opposites? How about turn it around, upside down, inside out? Other unexpected?	1. Maybe small hotwater/seawater container, but large fresh water container? 2. maybe a turnable / rollable device, which allows use of gravity and robustness?

Figure 6.2. A representative data sheet of ideation with SCAMPERR

6.3.4. Ideation with General Analogy

Since analogy plays a vital role in the fundamental of cognitive science, it is natural that analogy is embedded broadly and deeply in creativity (see Chapter 3 for a detailed review of analogy in creativity). In this session, only a brief introduction of generic analogy is discussed beforehand, and an understanding of analogy is left to the individual thinker's experience. This is because although analogy has been proven to be effective in ideation when embedded in certain creativity tools such as TRIZ, Synectics and Biomimetics (see sector 3.4), analogy itself has yet to be systematically abstracted and integrated into an independent creativity tool. As an additional comparison experiment in this case study, thinkers are encouraged to apply general analogy as they understand it, in a non-systematic fashion, with the aim of seeing whether general analogy alone can be useful and the extent to which it is effective. A representative data sheet for idea generation with general analogy is illustrated in Figure 6.3.

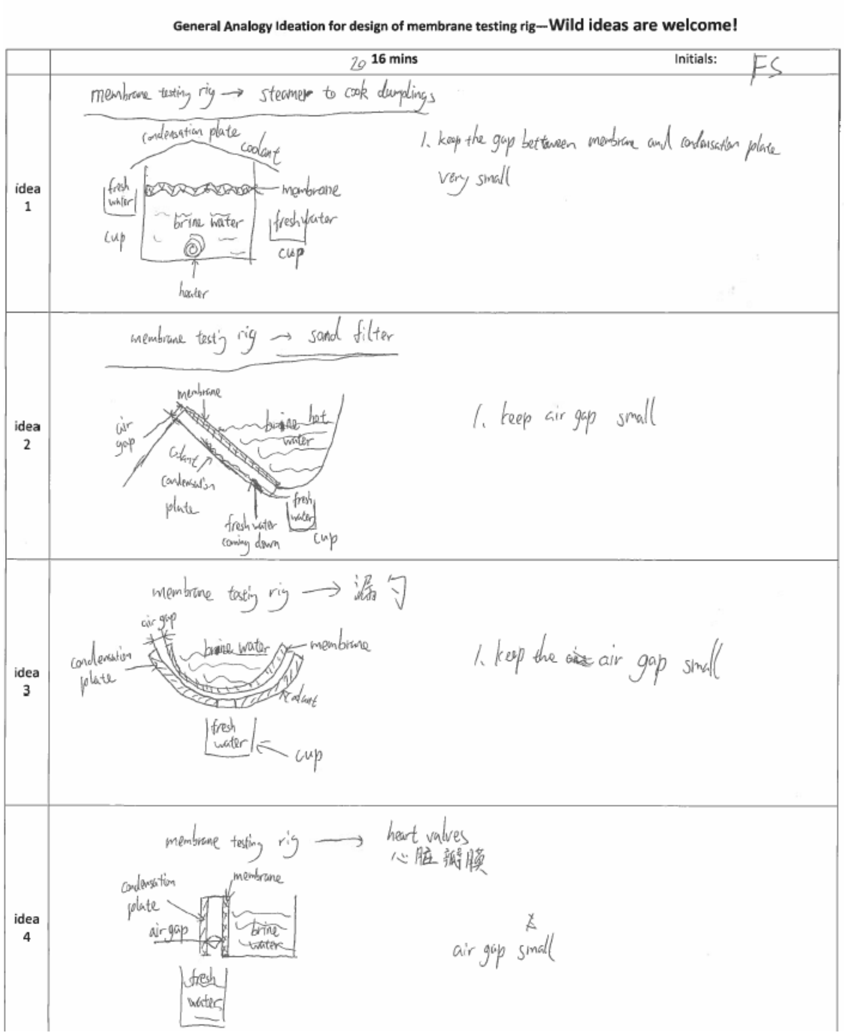


Figure 6.3. A representative data sheet with general analogy

6.3.5. Analogical Creative Process

Analogical Creative Process (ACP) has been developed based on previous studies on analogy establishment explained by Structural Mapping Theory (SMT) and Multiconstraints Theory (Gentner, 1983, Holyoak and Thagard, 1989), where relations between objects in both the base domain and target domain are prioritised over the attributes of subjects when mapping (see Chapter 5 for details of ACP).

Multiconstraints Theory further introduces pragmatic and semantic constraints to the mapping process seeking to identify analogies of a higher quality. The pragmatic constraint requires the thinker to have an approximately pre-defined purpose from the analogy, thus analogical mapping will take place under the guidance of the desirable direction. The semantic constraint provides a larger flexibility for mapping, as the similarity of elements of both domains is considered (Bartha, 2013). ACP agrees with all the core points of the abovementioned theories, while also suggesting that, for practicality, a more systematic approach perhaps should be helpful in guiding thinkers with elements of analogical thinking. In other words, two step-by-step guiding processes are introduced to thinkers for both the solution-driven and problem-driven scenarios. The advantage of ACP, in addition to its integrated use of analogical thinking, is that for utilisation it does not require from the thinker a deep knowledge of analogy or experience of analogical thinking because of its systematic step-by-step structure. The essence of ACP is to promote analogical thinking in a step-by-step form derived from the Structure Mapping Theory for establishment of analogy. Since ACP aims to promote analogical thinking whilst not limiting the choices of source domains for designers, the source domains for analogical mapping are chosen by the users. An example diagram of ACP is illustrated in Section 3.8. A representative data sheet with ACP is illustrated in Figure 6.4.

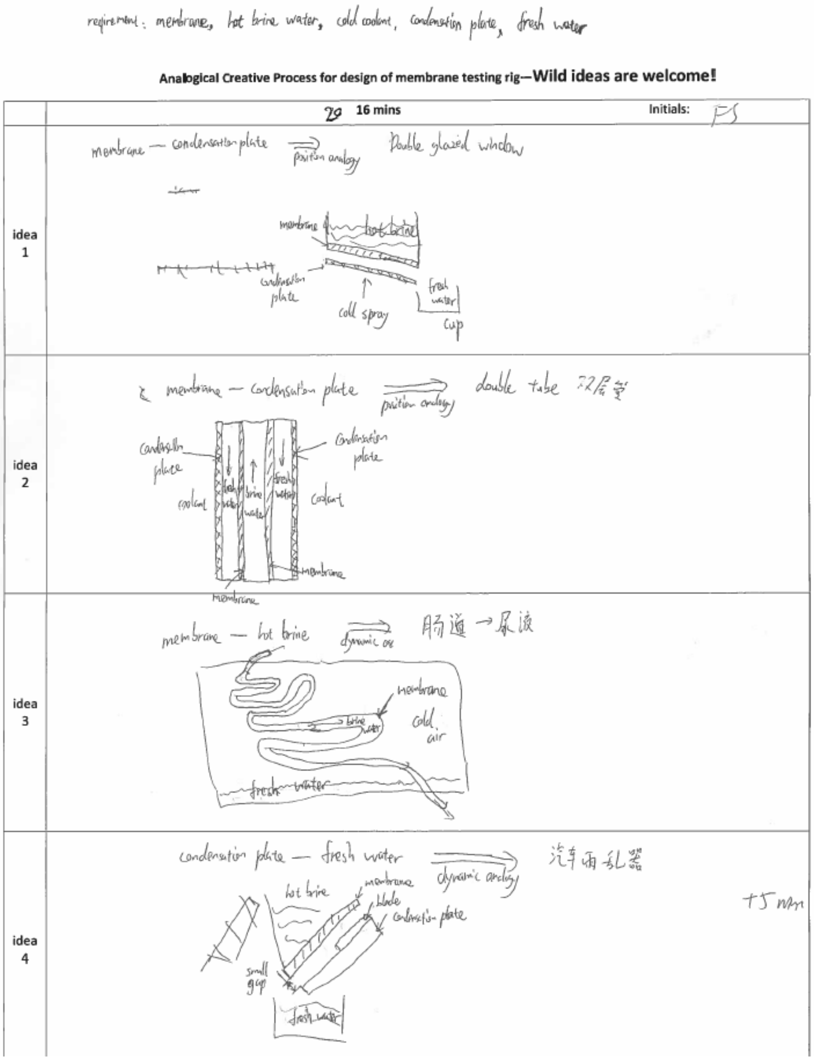


Figure 6.4. A representative data sheet with ACP

6.4. Data analysis

As previously discussed, this case study applies an exploratory sequential approach of Mixed Methods Research, which examines findings of convergence and consistence with the research. It is important to review the findings from other literature on analogical thinking in creativity and design. Equally important is to investigate how analogy is applied in practical workshops.

6.4.1. Literature review of findings from analogy studies and workshop

a. Findings of analogy and analogical thinking in design and creativity literature

The value of analogy and analogical thinking are widely reported in research on product design and engineering innovation (Dahl and Moreau, 2002, Christensen and Schunn, 2007, Gassmann, 2008), general creativity and problem solving (Qian and Gero, 1996, Casakin and Goldschmidt, 2000, Bonnardel, 2000). In such research, various methodologies are adopted including qualitative, quantitative, a mix of qualitative and quantitative, combinations of qualitative and quantitative, as well as Mixed Methods Research. Research by case studies utilising analogy ranges from graphic design to design in architecture, from industrial design to engineering design, and from practitioners of art students to professional design companies. Some of these case studies investigated the use of analogy by various of thinkers, from a group of applied art students to professional design consultants, as well as the use of analogy within companies of different sizes i.e. from ones with several hundred employees to ones with tens of thousands employees (Gassmann, 2008). These findings coincide with the assumption raised by the research questions for this study. Analogy and analogical thinking are deemed effective subject to internal and external conditions.

As pointed out in Section 3.6, a positive correlation has been identified between the amount of analogical thinking, the analogical distance and the novelty and originality of design results (Dahl and Moreau, 2002, Kalogerakis et al., 2010). Close analogies, although still powerful in ideation, seem to be found to be less effective compared to distant analogies in terms of the novelty of design by this research. Findings from another study indicates that the quality of ideas generated using analogy has proven to be higher with near analogies compared to far analogies, and this contradicts previously cited findings. However, a clearer implementation of data collection strategy would increasingly benefit the result on its creditability (Chan et al., 2015). It has been suggested that the correlation between ideation quality and analogy distance is dependent to the individual design project, based on the finding from a study using crowdsourcing as data collection method (Goucher-Lambert and Cagan, 2017). As far as quantity and quality of analogies are concerned, the trend is that, more analogies are generated when multi-base domains are used compared to a single base domain; while analogies from local general knowledge source are efficient in design ideation, and analogies derived by designers from existing technological solutions or functions tend to be more effective.

A review of the literature also suggests that analogy can benefit the design of different domains by provoking general innovation. One systematic attempt to generalise analogical process for problem-solving is to establish a formalism using analogical mappings at Function-Behaviour-Structure level, so that analogy can be used to help produce new design from different design domains (Qian and Gero, 1996). This formalism introduces in-depth mechanisms to form analogical mappings, yet its complexity in use can cause a negative effect on practicality in analogical design ideation. One challenge to applying analogical thinking in design is the lack of suitable methods to identity and establish the analogical connection between domains (Nagel et al., 2018), which encourages the proposed application of ACP in engineering design and enterprise design as a guidance method.

Experienced designers and novice designers can be distinguished by their use of analogy, although analogy is reported to be effective in both groups. Experienced designers tend to adopt a more general design approach compared to novice designers who are more centred on the specific design task (Bonnardel, 2000). As a result, on one hand, both experienced and novice designers can benefit from using analogy in design projects with guidance and the deliberate use of analogy achieves better results (Casakin and Goldschmidt, 2000). On the other hand, while analogies from local general knowledge source by novice designers are efficient in design ideation, those derived by experienced designers from existing technological solutions or functions tend to be more effective (Kalogerakis et al., 2010).

b. Investigation on experience design workshop for behavioural change using analogical thinking

This one-day workshop held at the Royal College of Art (RCA) consisted of two key contents (see Appendix 2). 1) To conduct both general ideation and ideation with analogical thinking for comparison; 2) To investigate analogical thinking in guided environment. Analogical thinking is promoted and tested at the workshop with utilisation of APISNOTE, a web-based tool for post-it ideation (Figure 6.5).

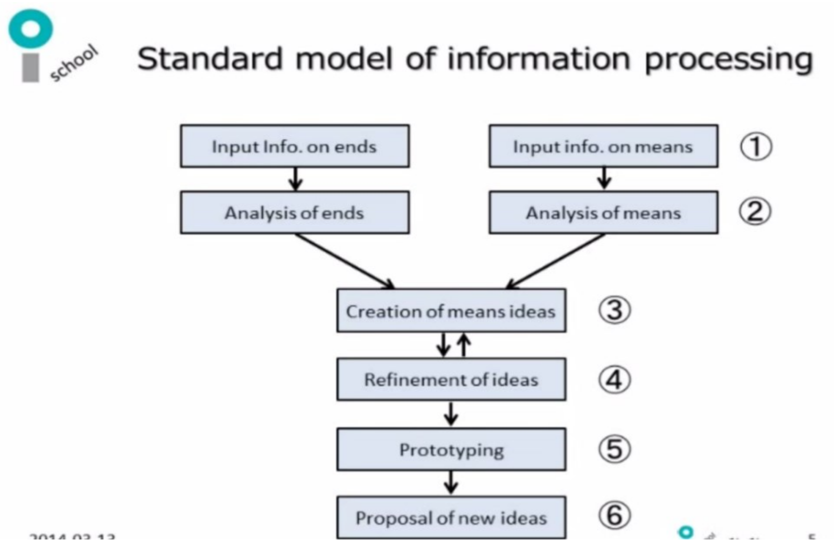


Figure 6.5. Model of information processing

For comparison of general ideation and ideation with analogical thinking, the scenario of a shopping mall is adopted. At the stage of general ideation, a five-minute video of a shopping mall is played, and the participants are encouraged to generate as many ideas of potential services that could be provided in the shopping mall as possible. This general ideation exercise is effectively brainwriting with assistance from software.

Brief training is provided prior to ideation with analogical thinking, with the example between the online book merchant business sector of Amazon and conveyor belt sushi bar being introduced to demonstrate analogy, where both have the mechanisms of tracking product acceptance and analyse data for future marketing (see Figure 6.6, Appendix 2). Here, an analogical mapping is clearly established between source domain (Amazon) and target domain (Conveyor belt sushi bar). No attributes are mapped over, but instead the mechanisms for collecting data from previous marketing events and using the data for future marketing is the relation that is mapped over between the domains.

Taylormade proposal

Amazon	Conveyor belt sushi bar
Books	Sushi
Click buttons or browse pages	Insert dishes with QR code or IC tag on the back
Provided Value ・Propose books of my favorite	Provided Value ・My favorite sushi comes when I want it.
Mechanism of value provision ・Database of information browsing history and purchase history and analysis of similar customer data	Mechanism of value provision ・Database from QR code or IC tag attached to the back of the dishes and analysis of similar customer data
Incentive of data provision ・Just browse and buy	Incentive of data provision ・Just eat

Figure 6.6. Analogical mapping between Amazon and Conveyor belt sushi bar

The participants are then encouraged to watch the same video of shopping mall for three minutes for ideas of potential available services, with the aim of generating ideas by analogical thinking. According to the feedback from groups, the idea generation with analogical thinking feels easier compared to general divergent ideation, and the quality of analogical ideas have a higher degree of novelty and usefulness.

The workshop further investigated on behaviour change by ideas generated using analogical thinking, where the ideation groups were provided with step-by-step guidance for analogical ideation. The qualitative results indicate that guided ideation contributes to more novel ideas and the user experience feedback is more positive compared to free non-guided ideation.

The workshop provides qualitative evidence that analogical thinking works well for guided ideation, even among participants with a little or no experience or training. This conclusion coincides with the relevant literature on usefulness of analogy and analogical thinking in creativity and design, and helps to examine the research questions raised for the desolinator case study on analogical thinking.

6.4.2. Data analyses for desolinator ideation data

As previously discussed, rather than searching solely either quantitative or qualitative indications from the data collected, this case study seeks to identify whether an extra level of effectiveness is introduced by analogical thinking compared to non-analogical ideation. It would be crucial to measure the outcome of ideation along with the process of ideation to obtain a richer image. However, it would be difficult to solely rely on the ideation process for evaluation of effectiveness, as protocol studies and cognitive models are compulsory with heavily repeat of processes (Shah et al., 2003). Therefore, in addition to the analysis for ideation outcomes, post-ideation surveys and feedback interviews are carried out. Four measures of ideation effectiveness are adopted in order to evaluate the overall effectiveness of both analogical and non-analogical based activities: quantity, quality, novelty and variety. Quantity measures the total ideas generated by each thinker in the sense that larger amount of ideas is more likely to contain more creative ideas. Quality measures the technical practicality and feasibility of ideas generated. Novelty measures the unexpected surprising elements in ideas as they differentiate themselves from less unusual ideas. Variety measures how well the thinker is exploring the design solution space and similar ideas therefore indicate a lower level of variety (Shah et al., 2003). The four measurements are focused on each individual thinker and endeavour to discover any consistency in the results. Group ideation effectiveness is not analysed for this study as there is no difference in ideation environment for thinkers; moreover, effectiveness of tools on individual effect is a core study subject. The data is logged and analysed from Table 6.5 through to Table 6.9. It is worth noting the difference on calculation of the scores for the four measurements. Quality and Novelty scores are assessed by the value of each idea by the same assessor using scale of 1 to 10, where 10 is highest score. Quantity and Variety scores are obtained by the overall evaluation of collection of ideas; quantity is directly recorded while variety is then represented by scoring system of 1 to 10 with 10 as highest. The final values of quality and novelty are averaged from all the figures.

A	Non-analogical		Analogical	
	Brainwriting (original+	SCAMMPERR	General analogy	ACP

	elaboration)			
Quantity	25 (5+20)	24	4	6
Quality	7.36	8.13	7.50	6.83
Novelty	5.24	3.50	6.50	7.00
Variety	6	5	8	7

Table 6.5. Measurements of tool effectiveness for thinker A

B	Non-analogical		Analogical	
	Brainwriting (original+ elaboration)	SCAMMPERR	General analogy	ACP
Quantity	24(5+19)	18	4	4
Quality	7.29	7.61	6.75	6.50
Novelty	5.42	3.06	7.00	7.25
Variety	5	5	8	8

Table 6.6. Measurements of tool effectiveness for thinker B

C	Non-analogical		Analogical	
	Brainwriting (original+ elaboration)	SCAMMPERR	General analogy	ACP
Quantity	23 (5+18)	15	4	5
Quality	6.74	7.07	6.50	6.80
Novelty	4.91	3.73	5.25	5.20
Variety	4	5	7	6

Table 6.7. Measurements of tool effectiveness for thinker C

D	Non-analogical		Analogical	
	Brainwriting (original+ elaboration)	SCAMMPERR	General analogy	ACP
Quantity	25(5+19)	19	4	4

Quality	7.56	7.37	6.25	6.00
Novelty	3.80	3.42	6.00	6.50
Variety	4	5	6	6

Table 6.8. Measurements of tool effectiveness for thinker D

E	Non-analogical		Analogical	
	Brainwriting (original+ elaboration)	SCAMMPERR	General analogy	ACP
Quantity	43(5+38)	22	4	5
Quality	6.09	7.32	6.25	6.40
Novelty	5.28	3.32	6.75	6.60
Variety	5	5	7	6

Table 6.9. Measurements of tool effectiveness for thinker E

A list of major findings can be observed by the collection of Tables.

a. The quantity of ideas generated by non-analogical tools is larger than that generated by analogical tools. The prime reason would be that both brainwriting and SCAMPPERR are designed to generate a large amount of ideas as they encourage divergent thinking, but they do not require a thorough consideration of each idea generated as a higher level of comprehension would slow down the ideation. Analogical tools, conversely, require thinkers to map between the base and target domains more carefully with either intuitional (general analogy) or systematic (ACP) thinking. Another reason for higher volume of ideas generated by non-analogical tools is that thinkers are allowed with very brief idea descriptions and ideation for aspects of the whole of membrane testing rig, which also helps to lead to a larger quantity.
b. Although a small difference, the quality of ideas generated by non-analogical tools exceeds those generated by analogical tools, especially when using SCAMMPERR. The term 'Quality' here refers to the technical practicality and feasibility of ideas in design, therefore the differences indicate that ideas generated by SCAMMPERR in this study appear to be more practical and

feasible in realisation. SCAMMPERR's high score in quality is expected as it provides specific guidance of thinking in a highly practical setting.

c. Higher novelty of ideas generated is achieved by analogical thinking compared to non-analogical thinking in this study. This result coincides with the literature which argues that analogical thinking leads to novel ideation as it investigates the structures of both base and target domains for mapping (Moreno et al., 2016a, Christensen and Schunn, 2007). Little difference of novelty between general analogy and ACP is observed from this study as the size of data sample is limited. The specific guidance of SCAMMPERR results in the lowest score in novelty, because the provided thinking direction could limit the diversity of ideas, although is helpful in offering thinking suggestions.
d. Variety scores of analogical thinking exceed non-analogical thinking, without exception. The main reason for this is that analogical thinking, be it intuitional general analogy or systematic ACP, attempts to concentrate on the quality of mapping between base domain and target domain, whilst distant (far) analogies tend to lead to a higher novelty compared to close (near) analogies (Kalogerakis et al., 2010). When the thinkers endeavour to establish analogical mappings between much distinguished domains, the variety of ideas then increase.

6.4.3. Post-ideation interview and feedback on analogy quality

Post-ideation interviews and questionnaires for feedback are important factors to consider and understand the performance of both non-analogical ideation and analogical ideation. The investment theory on creativity from domain of cognitive psychology indicates that creativity is associated with six factors: intellectual skills, knowledge, thinking style, personality, motivation and environment (Sternberg, 2006, Sternberg and Grigorenko, 1998, Sternberg and Lubart, 1991, Kaufman, 2019). Therefore, for the purpose of comprehension, it would be necessary to carefully design the post-ideation questionnaire in such a way that all six factors associating creativity are involved.

A questionnaire investigates the thinkers' feedback from personal, performance, self-perception and contextual angles with detailed rating factors as illustrated in Table

6.10 (Moreno et al., 2016a). Rating attributes for all factors are recorded with a numerical scaling system from 1 to 5, where 1 represents the extreme negativity in attributes while 5 represents extreme positivity.

Factor source	factors	Rating attributes
Personal	Entertainment	Boring—Fun
	Motivation	De-motivating—Motivating
	Inspiration	Frustrating—Inspiring
	Easiness	Difficult—Easy
Performance	Commitment	Minimal effort—Worked hard
	Concentration	Unfocused—Focused
	Success level	Unsuccessful—Successful
	Pressure level	Unrelaxed—Relaxed
Self-perception	Usefulness	Useless—Useful
	Easiness	Difficult—Easy
	Meaningfulness	Meaningless—Meaningful
	Importance	Unimportant—Important
	Confidence	Unconfident—Confident
Contextual	Time	Insufficient time—Sufficient time
	Environment	Unrelaxed—Relaxed

Table 6.10. Illustration of factors for post-ideation feedback

The post-ideation feedback and questionnaire aim to learn more about the thinkers' subjective views on the ideation practice, and whether the feedback indicates a correlation between actual ideation performance and thinkers' perception under investment theory is also of interest to the researcher. The key is to identify the qualitative tendency of any correlation rather than the quantitative calculation. The observation from data does not indicate a clear correlation between ideation performance and thinkers' perception, which could be due to the limited sample size of this study; therefore, it does not necessarily contradict the investment theory. In fact, for both analogical tools of which novelty and variety score exceed non-analogical tools, the feedback indicate higher scores for factors under performance and self-perception categories. This observation indicates that for this study, thinkers feel positive in subjective performance rating and self-perception while actual ideation result coincides with such views. It is suspected that, although analogical thinking is less usual for thinkers in this study, elements of its structure mapping between the base and target domains echo thinkers' self-perception on performance. This finding not only suggests that analogical thinking can benefit ideation, but actually provides new potential methods for further studies to encourage better ideation performance, which are to enhance thinkers' self-perception and satisfaction of work by giving a positive indication of related factors.

6.5. Conclusion and discussion

This study aims to identify the value of analogical thinking in conceptual design ideation for a real-world engineering design project. A well-established methodology of Mixed Methods Research is adopted with findings which answer the two research questions raised. In this study, analogical thinking has been proven to be effective in ideation, particularly in providing higher degrees of novelty and variety in ideas generated compared to the ideas generated by non-analogical tools of brainwriting and SCAMPPERR. Higher degrees of novelty and variety of ideas generated by analogical thinking have been observed and recorded. Both more intuitive general analogy and more systematic Analogical Creative Process are used in this study and the ideation results remain consistent. It can be concluded that, due to the extra novelty and variety, the use of analogical thinking in design ideation compensate the sole use of non-analogical tools.

This study also observes some evidence for the investment theory of creativity, where thinkers' self-perception of performance coincides with actual ideation performance with use of analogical tools. Qualitative analysis of post-ideation feedback and questionnaire indicate that when thinkers feel more motivated and are interested in analogical methods, greater positive performance results can be expected, irrelevant of the difference of cognitive style, intellectual ability and knowledge. The impact of elements including motivation to creative output is expressed in a theoretical framework (McCarthy, 2019), and positive correlation between thinkers' intrinsic motivation and creativity performance is also reported in a research on R&D engineers (Zhu et al., 2018). These findings would further enhance the outcome of ACP by correlating positive experience of ideation with analogical thinking. Potentially, with further studies carried out in this direction, this could lead to discoveries of enhancing thinkers' performance by pre-enhancing their confidence, expected level of fun and motivation prior to ideation.

The understanding obtained of analogical thinking featuring ACP in this case study is the primary output of this chapter of the research. Meanwhile, new insights of evaluation of analogical thinking comparing to non-analogical thinking in this given context of engineering design is derived, through the application of ACP, which works as a novel approach of utilising analogical thinking. The clear step-by-step guidance of ACP and its focus on mapping of functions lead to the successful application in the real-life engineering design project. The reported discoveries from this study contribute to the research of conceptual ideation in engineering design in that, extra merit of quality and novelty are identifiable when analogical thinking is utilised, and this conclusion is supported by the guidance from MMR for research methods. As the result of the creative ideation featuring analogical thinking, the working prototype for the concept design has been achieved as illustrated in Figure 6.7, which fulfils the primary technical requirements specified by the clients.

Figure 6.7. Working prototype for the desolinator design

This use of a real-world system design project as a case study for creative thinking in ideation has numerous merits: a) it provides real-world design boundaries and practicality; b) the ideation is expected to lead to actual design; and c) thinkers tend to be more motivated with clear targets. However, there are drawbacks for such studies caused by limited resources and time. On balance, this study concentrates more on qualitative than quantitative element of research within the setting of Mixed Methods Research, in order to try to avoid overstated findings. The results and conclusions coincide with a relevant literature review, the collected data and the existing theory. Leading to better serving the purpose of creative ideation for conceptual design phase, further studies could endeavour to identify whether positive insinuation and improvement of environment have a positive effect on thinkers' ideation result in an engineering design context.

Chapter 7. An analogy-empowered creative process for Design of Enterprise

From the foundation of the knowledge obtained on creativity and analogy in Chapters 2 and 3, as well as the understanding gathered from a real-world engineering design project in Chapter 6, this chapter argues it is feasible to propose an analogy-empowered creative process to enhance design, which when integrated with additional key elements is deemed valuable by the researcher. The application of such a process in enterprise design is suggested and explored in Chapter 8, provided that the existence of analogical thinking is identified through data collection and analysis presented in this chapter.

7.1. Introduction

This chapter explores enhancing the creative design process by utilising analogical thinking, so that the creative output is improved in design. It aims to demonstrate the value of analogy and analogical thinking in establishment and development of enterprises including start-up companies, Small and Medium Enterprises (SMEs), and large businesses. The term "design of enterprise" here consists of two meanings: 1) Enterprise as the object of the activity of design, similar to design of product or design of systems, where a real-world oriented enterprise is the aim and deliverable of design activities. 2) To create the enterprise through a design process led by design thinking and design methods. This is meant to be a creativity-enhanced attempt for the establishment of enterprise compared to what is traditionally a business approach. Creativity is integrated to form a creative design process, and analogical thinking is promoted to enhance creativity. Data has been collected by both the literature review of enterprise and interviews of key personnel of enterprises in order to identify analogy in the design of existing enterprise, which is a key indicator of value of analogical thinking in enterprise. Proposals have been made to integrate analogical thinking as an essential element towards the design of sustainable enterprise.

This chapter analyses the use of analogy in the environment of SMEs and large businesses which are solely distinguished by company size. The rationale behind the choice of the research objects is derived from the business size structure in the UK, which is illustrated in Table 7.1 (Rhodes, 2018). The SMEs are considered as businesses with fewer than 250 employees, where Micro is fewer than 10 employees, Small is 10 to 49 employees and Medium is 50 to 249 employees. Large businesses employ minimum of 250 employees. All numbers in Table 7.1 are rounded to the nearest 1000. In 2018, the quantity of SMEs in the UK accounted for over 99.9% of the total number of businesses, which indicates the significance of using SMEs as research object for enterprise design study. However, large businesses employ 40% of total employees in the UK and generate 48% of the total turnover, making it meaningful to investigate the use of analogy by business leaders of well-known large business.

	Businesses (1000s)	Employment (1000s)	Turnover (£billions)	Business	Employment	Turnover
Micro	5416	8082	808	96%	33%	21%
Small	210	4083	590	4%	15%	15%
Medium	35	3399	595	1%	13%	15%
SMEs total	5660	16284	1994	99.9%	60%	52%
Large	8	10743	1868	0%	40%	48%
Total	5668	27027	3862	100%	100%	100%

Table 7.1. UK business quantity by sizes in 2018 (adapted from Rhodes, 2018)

This research aims to promote creativity within the setting of the design of enterprise. The integration of analogical thinking, which helps to encourage creativity, into the proposed model for the design of enterprise, is expected to lead to innovation in design output. Creativity and innovation are the driving forces of the modern business world. A Business Insider article compiled a list of 15 US-based start-up companies, which were founded between 2012 and 2016 and valued by capitals by December 2016 at a minimum of 1 billion USD. The list suggests that the creative disruption into the traditional industry such as real estate and software could create huge business success and innovative impact to people's life (BusinessInsider, 2016). It should be accepted that presence of creativity and innovation will benefit an enterprise in long-term development, as innovation contributes to improvement of product and service, thus enhances the enterprise's competitiveness. Open innovation and creative thinking, along with expertise and motivation, are argued to contribute to productivity and efficiency of an enterprise (Serrat, 2017). The historical development process of human civilisation has been driven by human creativity and acts of innovation. For enterprise, it has been reported that innovation, especially open innovation tend to be positively related with enterprise growth by increasing enterprise effectiveness and efficiency (Rexhepi, 2019).

This chapter adopts a triangulation of research methods for the intended deliverable of an analogy-empowered creative design process. The literature review on design processes is conducted to gain in-depth understanding of the design process being used in the company concerned and associated insights; a qualitative investigation of the value of analogy in development of enterprises indicates whether analogies exist in the development process of enterprises; and strategic quantitative analyses of data collected through the qualitative reviews of published documents and publicly available interviews assists in enhancing the findings.

This chapter starts by reviewing the existing models of engineering design and suggesting a framework for creative design of enterprise; then, analogy-driven creativity is identified in real-world cases of design of enterprise; this preparational work subsequently leads to a proposal to integrate analogical thinking as an essential element for design of sustainable enterprise.

The intended support developed by the study and reported in this chapter is a proposal for the design of sustainable enterprise featuring an analogy-empowered creative design process. The integration of the process consists of three key elements: creativity, analogy and the design of enterprise; the relations between the elements are illustrated in Figure 7.1.

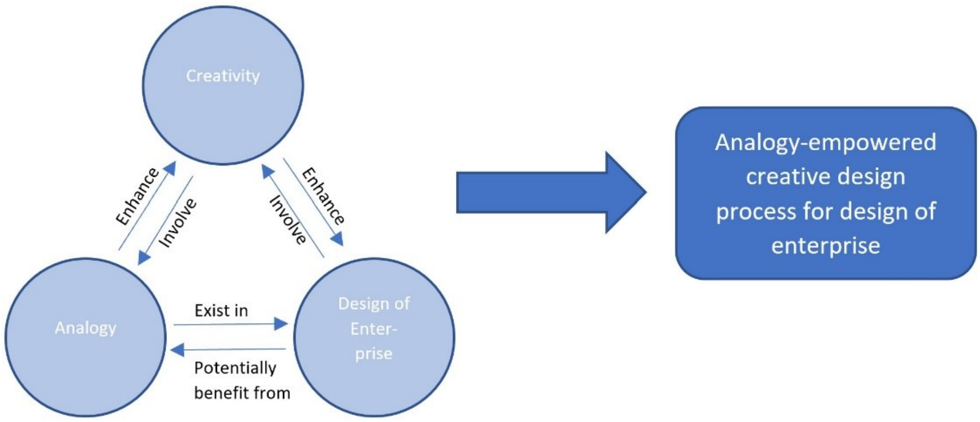


Figure 7.1. Relations between key elements within proposed design process

Analogy has been identified in research of creativity and design as an important element. This study would like to promote analogy by having it embedded in the creative design process for improved design output.

7.2. A creative design process for the design of enterprise

7.2.1. Review of the design of enterprise

The design of enterprise in the context of this research endeavours to focus on both means and ends of the design activity. In this context, the means relate to the design process for establishment of an enterprise, i.e. the translation and bridge from the expertise of entrepreneur to the deliverable outcome of a commercial enterprise, following the chosen model of design process and led by design thinking. Ends signify the realisation of enterprise as the object of design, where normal commercial criteria apply, including market requirements, products and services, customer experience and sales.

Design-led innovation and commercialisation have resulted in positive outcomes in entrepreneurship and user experience, where the Double Diamond Model was adopted for design-led divergent-convergent framework (Leon et al., 2012, Nicolettou et al., 2016). The European Commission has developed a three-year course on design for enterprise for SMEs development, featuring design-led innovation as a tool and customer-centred design, in order to sharpen the EU businesses' skills and thus increase competitive ability (EuropeanCommission, 2015). Attempts were made to create a detailed 20-step design process to enable creativity from management angle (Chapman, 2006), although abstraction for a generic model has not been proposed.

The design process is described as “a labour intensive process culminating in the proposal of a product or process”, while the creativity process is described as “a cognitive process culminating in the generation of an idea” (Howard, 2007). The comparison between an engineering design process and a creativity process indicates similarities, differences and the possible integration of the two processes. The similarities include the common expression by linear-structured models, the integration of divergent and convergent phases, the description of spaces, where the design process refers to the information space while the creativity process refers to problem and solution spaces; both processes typically start with phases of analysis of problem or task. The differences mainly exist in the scope of the two processes, where design process requires the delivery of design solutions while creativity process focuses on evaluation and validation of the idea generated. Due to the structural and essential similarities between the two processes, an integrated creative design process could in theory combine the strength of creativity with the systematic design process, resulting in a generic design process enhanced by creativity.

7.2.2. Applicable elements from models for design process

This section reviews and analyses three established models for design process, all of which have prioritised elements that merit being abstracted and integrated into the subsequently proposed creative design process. These elements are divergent-convergent thinking, human-centred element and the comprehensive structure for a design process.

a. A Double Diamond model is adopted by the Design Council to illustrate the design process (Figure 7.2) (DesignCouncil, 2005). The model reflects the use of divergent and convergent thinking, and consists of four phases: Discover, Define, Develop and Deliver.

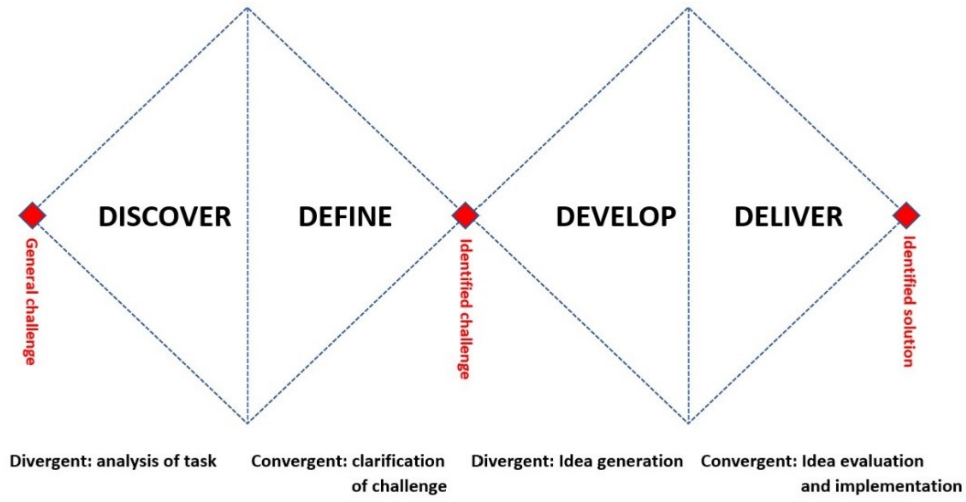


Figure 7.2. Double Diamond model for design process

Divergent thinking is likely to help generate creative ideas as the thinker is encouraged to generate large amount of ideas; convergent thinking assists in the selection of the best solution as evaluation of ideas are involved. Both divergent and convergent thinking are compulsory phases in this model and are repeated in each diamond for completed problem-finding and solution-finding. The divergent and convergent thinking are iterated twice to form a double diamond roadmap for the design process. The content and suggested methods for each phase are shown in Table 7.2.

Phase		**Content**	**Useful Methods**
Diamond 1	Discover	Divergent thinking; involving market research, management of team and information	Creating a project space, Observation, Interview, Market specification identification, Brainstorming, Quantitative surveys, Fast visualisation, Secondary research, Hopes and fears
	Define	Convergent thinking; involving project development and management	Focus groups, Assessment criteria, Expert evaluation, Comparing notes, Drivers and

			hurdles, Customer journey mapping
Diamond 2	Develop	Divergent thinking; involving realisation of design with method development	Character profiles, Scenarios, Role-playing, Service blueprints, Physical prototyping
	Deliver	Convergent thinking; involving final approval and launch of enterprise with evaluation	Phasing, Final testing, Evaluation, Feedback loops, Methods banks, Market trials

Table 7.2. The four phases of Double Diamond model for the design of enterprise

The Double Diamond model as a design process is applicable to the development of products, services and enterprise, as the model offers dedicated phases for both divergent and convergent thinking in both problem and solution space. In the practice of the design of enterprise, it is important to explore the problem-finding phase as it could be easily neglected, resulting in the development of product or service solutions not fitting strategically with the requirements. The Double Diamond model, along with controlled convergence (Pugh, 1991), forms the divergent-convergent thinking in design, which echoes the integration of creativity into the design process, as the convergent phase requires an evaluation of ideas.

b. The Stanford d.school introduced an alternative model for design thinking process with strong elements of human-centration (d.school, 2010). The process consists of five key modes: Empathy, Define, Ideate, Prototype and Test, as shown in Figure 7.3. Human-centred thinking and activities are highlighted in each mode throughout the process, while divergent and convergent thinking are immersed within the process. The feelings, experiences and feedback of the users are investigated within each mode to guide the design outcome, with the aim of offering new insights to be gathered through interaction with users and the best design solutions to address the real needs of the users. The human-centred elements of this process are to be integrated into the proposed creative design process as an important feature, with the aims and suggest activities in each mode described as follows.

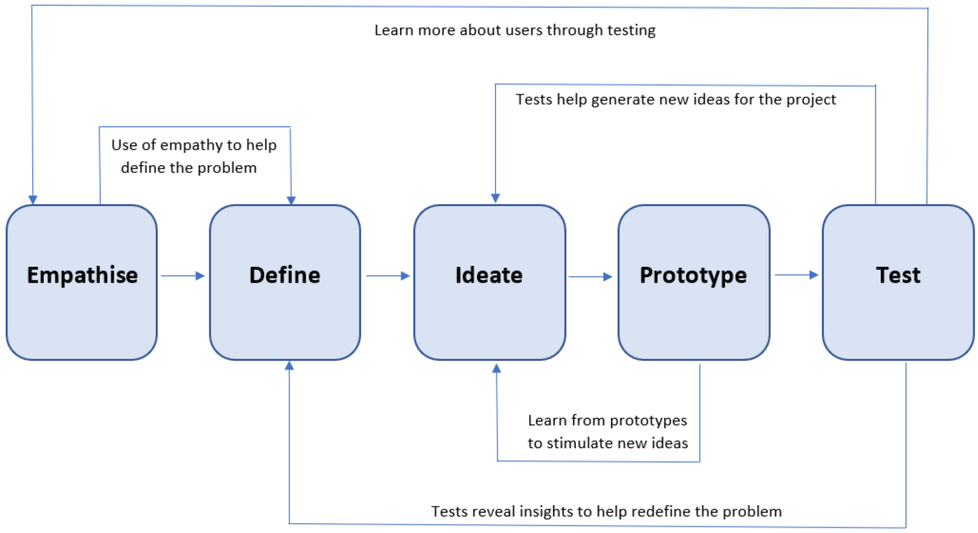


Figure 7.3. The five key modes in a human-centred design process

- Empathise

The aim of empathy as a mode in the creative design process is to gather more insights from the user and the interaction between the user and the design challenge. In the context of design of enterprise, to empathise means to explore the perception of clients, providers and competitors to obtain a thorough understanding of the business situation. Empathy also helps avoid the psychological fixation from the designers, which could lead to an inaccurate interpretation of the design problem, especially when designers are not experienced entrepreneurs.

The method of engagement is also tested and applied in interviews of the SMEs with useful findings. The combination of observation and engagement could help set the designer into the role of user and experience the challenge faced by the user, so that the definition of the design problem could be thorough and clear. This is particularly important for the design of enterprise practices as a “wicked problem”, where the identification of problem is unknown, possible solutions are unlimited, whether the problem has been solved through design activities is unclear, and problem reoccurrence could occur (Chan, 2015).

- Define

The mode of define aims to obtain a clear and comprehensive description of the design problem based on the understandings from the empathy phase. Compared to the observation and engagement activities from the mode of empathise, the insights derived from interpretation and synthesis of data is key. In the context of design of enterprise, the outcome of the phase of define would include clarification of market requirements, resources and challenges, team and project management, a risk and impact assessment and a business plan.

- Ideate

The mode of ideate concerns idea generation, as illustrated previously in Chapter 2, where both large quantity and variety of ideas are endeavoured. While creativity is involved in every stage of design process, idea generation is the phase where creativity is particularly sought after, and creativity tools can assist towards new and useful solutions for the design problems. Typical creativity tools for idea generation include brainstorming, morphological analysis, TRIZ and Synectics. Analogical thinking tools such as ACP are suggested to be utilised because Ideation is about divergent thinking for as many ideas as possible, and no evaluation or judgement should be involved as the restrictions they bring in could comprise the idea novelty.

In transition between Ideate and following Prototype mode, a selection process of ideas should be considered to make prototype of. This process echoes with the convergent phase and requires enterprise designers to select from ideation outcome on all aspects of business development, including market awareness, management of resource and team, impact and risk assessment and plan for business development.

- Prototype

The mode of prototype aims for the realisation of ideas by producing overall business plans that provide an improved understanding of design requirements. In the context of the design of enterprise, the ideas are selected as solutions for aspects such as product and service development, management of team and resources, and risk assessment; the solutions then form a deliverable enterprise prototype. Prototyping, as an inexpensive trial and error approach, also ensures the management of solution-finding process in the sense that a complex problem could be divided into modular tasks to seek for solutions.

In the design process of an enterprise, feedback from and communication with all stakeholders including clients, advisers, designers and entrepreneurs help towards the improvement or re-design of product and service, and hence enhance design (Mourtzis et al., 2018). Therefore, the Prototyping stage can form part of the evaluation for the final stage of problem solving within the design process.

- Test

Due to the ever-changing nature of business world, through testing, more understanding of the users' needs may become available, and more potential improvements of prototypes could emerge, and these all lead to iteration of other phases in order to deliver the best solutions for the design task. The insights from the stakeholders' feedback would then help towards better understanding of the task and refinement of the prototypes and solutions. Invaluable testing results could be obtained by realisation of the enterprise as a real-world business with actual business activities.

The design process from d.school values empathy and prototyping, with human-centred element embedded in each of the five modes. The process also encourages iteration both within each mode and the circle of the steps. The linear appearance of the process does not restrict the pattern of utilisation of this model. As long as the human-centred element and the iteration are preserved, the design process can benefit specific design tasks including the design of enterprise. The human-centred element is to be preserved and appreciated in the integrated creative design process, especially when the process is applied in the design of enterprise, because of the rich communication and collaboration involved.

c. Total design model with updates

The total design model systematically describes design activities for product design consisting of phases of market, specification, conceptual design, detailed design, manufacture and selling (Pugh, 1991). A recent update of the total design model within the context of the design of enterprise has provided specific adaptions, as illustrated in Figure 7.4 (Childs, 2019). The framework of the total design model adaption suits the requirements in the design of enterprise satisfactorily and will be adopted as the structural framework for the proposed creative design process for enterprise.

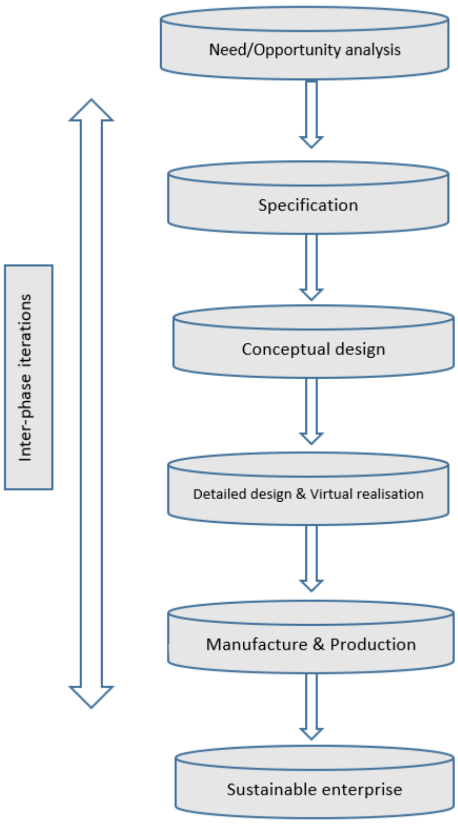


Figure 7.4. An update of total design model for the design of enterprise (Childs, 2019)

- Need/Opportunity analysis

  This phase involves a background search and identification of market requirements for a new product/service or an improved version of existing product/service, and can be referred to as opportunity identification, recognition of need or mission statement.
- Specification

  The specification phase aims to develop the design strategy and set boundaries for the following phases, it also requires the identification of resources and expectations of the design task. It entails the analysis and clarification of design task, investigation of need and developing product specifications.
- Conceptual design

  The conceptual design phase defines the functions, behaviours and structures of the task product, and aims to generate as many ideas as possible, and choose the feasible ideas through evaluation as outcome. Both divergent and convergent thinking are applicable at this phase to enhance idea generation and evaluation, respectively. As described in Chapter 2, the conceptual design should richly involve creativity tools to assist the creativity required for idea generation and evaluation. Analogical thinking, along with other creativity tools including Brainstorming (Brainwriting), TRIZ and morphological analysis, are likely to be utilised.
- Detailed design & Virtual realisation

  This phase concerns the realisation of conceptual design in order to test the outcome's technical functions, specifications and the requirements for manufacture. The phase may lead to the reapplication of previous phases including specification and conceptual design where changes or alterations need to be sought for due to challenges in detailed design phase.
- Manufacture & Production

This phase introduces the ultimate test on the outcome from conceptual design and detailed design phases as the concept, materials and structure must match the current manufacture capabilities and skills. The manufactured product needs to meet the requirements from specification and perform adequately for a reasonable life-span. In addition, the cost of manufacturing matters hugely and poor economic sustainability disclosed by manufacture phase could lead to redesign.

- Sustainable enterprise

  In this phase, the design outcome of the process is tested by the market response. A positive response from the market justifies all phases of design activities, while negative responses could indicate responsibility in any of the design phases. Therefore, careful planning and implementation at each design phase are essential to the expected deliverable outcome. The enterprise, as the entity of product and service provider, needs continued development in a sustainable fashion.

The total design model systematically covers a product design circle and contains, at each phase, prioritised design activities. However, it should not be a linear model with one-way implementation. The iteration between phases is necessary and useful in conducting changes, redefining specifications, and improving design solutions. The controlled convergence in concept design phase helps decide the best concept to work on in subsequent phases by paralleled ideation and evaluation (Frey et al., 2009). Iteration of the total design empowers it as a useful feature, which is embedded in the proposal of a creative design process in the subsequent sectors of this chapter.

7.2.3. Proposal of a creative design process for the design of enterprise

A review of a selection of sufficiently documented research on design process indicates that a linear style of process is commonly followed, as illustrated in Table 7.3. The conceptual design phase can be found in every process with essential functions for the design process to succeed. It has been established in previous chapters that creativity plays an important role in idea generation and evaluation in conceptual design phase. These observations lead to an elaborative attempt to integrate creativity practice into a generalised design process, so that design can benefit from creativity in a more systematic fashion. After all, design process as problem-solving process, when investigated with a cognitive psychologic perspective, generates systematic explanation with respect to how the information is searched, collected and processed by the design activities (Chan, 2015).

<table>
<tr><th>Models</th><th>Establishing a need phase</th><th>Analysis of task phase</th><th>Conceptual design phase</th><th colspan="2">Embodiment design phase</th><th colspan="2">Detailed design phase</th><th>Implementation phase</th></tr>
<tr><td>(Booz and Hamilton, 1968)</td><td>X</td><td>New product strategy development</td><td>Idea Generation, Screening & evaluation</td><td>Business analysis</td><td colspan="2">Development</td><td>Testing</td><td>Commercialisation</td></tr>
<tr><td>(Svensson, 1974)</td><td>Statement of need</td><td>Objective definition and analysis</td><td>Conception</td><td>Evaluation</td><td colspan="2">Modification</td><td>Decisions</td><td>Specification and organisation for manufacture</td></tr>
<tr><td>(VDISociety, 1982)</td><td>X</td><td>Planning</td><td>Conceptual design</td><td colspan="2">Embodiment design</td><td colspan="2">Detail design</td><td>X</td></tr>
<tr><td>(Pahl et al., 1984)</td><td>Task</td><td>Clarification of task</td><td>Conceptual design</td><td colspan="2">Embodiment design</td><td colspan="2">Detailed design</td><td>X</td></tr>
<tr><td>(Cooper, 1989)</td><td>Ideation</td><td>Preliminary investigation</td><td>Detailed investigation</td><td>Development</td><td colspan="2">Testing & Validation</td><td>X</td><td>Full production & market launch</td></tr>
<tr><td>(Pugh, 1991)</td><td>Market</td><td>Specification</td><td colspan="3">Concept design</td><td colspan="2">Detail design</td><td>Manufacture and Sell</td></tr>
<tr><td>(Hales and Gooch, 2004)</td><td>Idea, need, proposal, brief</td><td>Task clarification</td><td>Conceptual design</td><td colspan="2">Embodiment design</td><td colspan="2">Detail design</td><td>X</td></tr>
<tr><td>(Baxter, 1995)</td><td>Assess innovation opportunity</td><td>Possible products</td><td>Possible concepts</td><td colspan="2">Possible embodiments</td><td colspan="2">Possible details New product</td><td>New product</td></tr>
<tr><td>(Gassmann, 2008)</td><td>Strategic Intent</td><td>Abstraction</td><td>Analogy</td><td colspan="4">Assessment</td><td>Adaption</td></tr>
</table>

(Ulrich, 2008)	X	Strategic planning	Concept development	System-level design	Detail design	Testing, refinement and production
(Ullman, 2009)	Identify needs and design plan	Develop engineering specifications	Develop concept	Develop product		X
(Cross, 2008)	X	Exploration	Generation	Evaluation	Communication	X
(DesignCouncil, 2005)	Discover	Define	Develop			Deliver
(d.school, 2010)	Empathise	Define	Ideate		Prototype	Test
(Andreasen, 2015)	Exploration		Concept Synthesis	Product Synthesis and Development		Product Life Synthesis
(Eckert et al., 2017)	Project visualisation	Product visualisation	Product synthesis	Product analysis and evaluation		Product life cycle support

Table 7.3. Common phases of a selection of design processes

Previous researchers have determined that the creative process and the design process can be integrated together to form a creative design process. For instance, three variations of the creative design process are suggested to illustrate the value of creativity within the design process in design education (Wong and Siu, 2012). An innovative approach has been proposed to integrate creativity process into the design of enterprise to enhance the design outcome, as shown in Figure 7.5 embedded with the three elements discussed above. The three elements abstracted in the previous sector are also emphasised as key qualities of the process, including divergent-convergent thinking, human-centred element and the structure comprehensiveness of process.

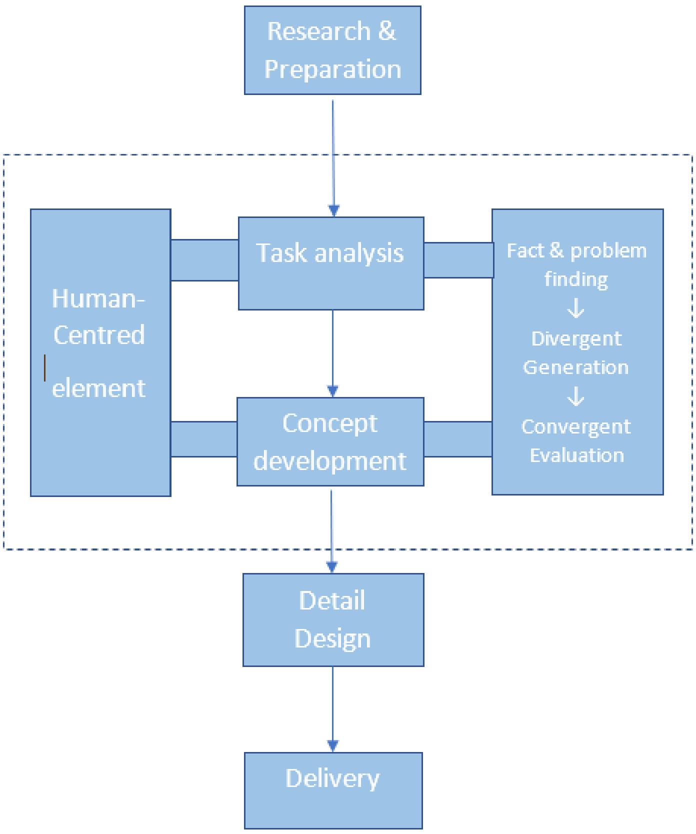


Figure 7.5. A proposed creative design process for the design of enterprise

The process starts with research and preparation phase, which refers to the initial market background research and preparation of understanding of all required resources, both which are available, and which are in need of acquiring. This phase is parallel to the "analysis of needs" phase in an engineering design process, and shares the same aim to any traditional development activity of enterprise, which is to understand the market needs and required resources. The outcome of this phase would lead to the informed decision of setting up an enterprise to fulfil the identified market gap.

It is at the “analysis of task” and “concept development” phases that the theory of Creative Problem Solving (CPS) joins in (see Section 2.1.2). The “fact-finding and problem-finding” in creative process echo with the “analysis of task”, and aims at identifying the challenges facing the designers in realisation of the enterprise. The challenges identified could be from the market requirement perspective, the technology perspective, or other perspectives. All the challenges and problems will be the objects of research that the following design phases attempt to solve.

Both human-centred element and divergent-convergent thinking are embedded into this phase, in order to achieve effective ideation outputs with the element of empathy. In practice as the design of enterprise is a wicked problem without a clear definition of problem or objective, the problem-finding and solution-finding activities are likely to evolve gradually during iteration. This anticipation echoes with existing findings in another research, where a co-evolution of problem-solution has been observed as illustrated in Figure 7.6 (Dorst and Cross, 2001). As explorations within the problem space and solution space proceed, the evolution of problem-finding is not only determined by the development of the problem space, but also considers the output from development within the solution space. This pattern is applicable to the requirements of design tasks of enterprise.

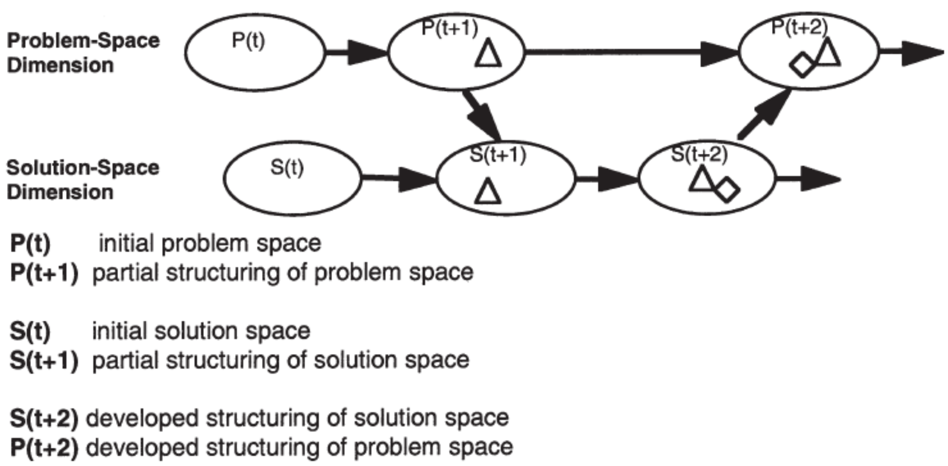


Figure 7.6. Co-evolution of problem-solution spaces

For each challenge identified at the “concept development” phase, both divergent thinking and convergent thinking are deployed for idea generation and evaluation, respectively. The divergent thinking and convergent thinking need to be iterated for identifying new insights from the findings and further elaboration. Creativity tools (see Chapter 2) are able to be adopted in this phase to assist development of creative solutions. Analogy and analogical thinking will be embedded into application at this phase in the following sections to enhance creativity.

Similar to an engineering design process, the “detail design” here refers to the realisation process from the outcome of concept development to feasible design outcomes. The difference is that the design outcomes will need to cover all object aspects of an enterprise, including the technology, market requirements, business development as well as on-going management. In addition, pilot launching of product/service at this phase should be considered, because the data collected would benefit the final phase of “deliver”, where the design outcome will be comprehensively and ruthlessly tested by the market. Broadly speaking, it is inevitable to experience caveats after the enterprise goes live into the market, and further development and optimisation are always necessary. However, the thorough testing and piloting of all aspects of designed enterprise before the “deliver” phase is recommendable.

The proposed creative design process for enterprise decides to integrate the three elements of divergent-convergent thinking, human-centred element and structural comprehensiveness, because not only these elements form essential functions in creative process and the design of enterprise, but also they are well-established and verified. For the refinement purpose for the proposed model, other approaches to integrating creative process with design process are also investigated, including an integrated creative design model based on the Function Behaviour Structure (FBS) framework (Gero and Kannengiesser, 2004, Gero, 1995) and combined with creativity process elements of Analysis, Generation and Evaluation, as illustrated in Figure 7.7 (Howard et al., 2008).

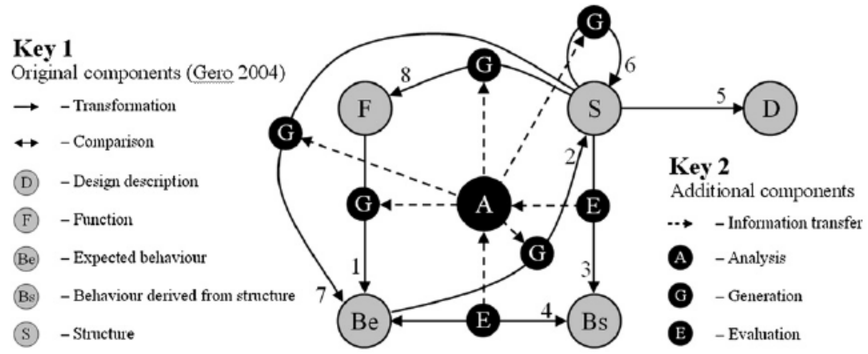


Figure 7.7. An alternative model for creative design process (Howard et al., 2008)

This alternative model is a valuable attempt to integrate the engineering design process and the creative process from the domain of cognitive science. However, in order to present the proposed creative design process for enterprise in a more user-friendly linear manner and to emphasise the chosen three elements, this alternative model is not adopted in this occasion.

7.3. Analogy identification in the development of enterprises

7.3.1. Introduction

This empirical study forms a part of the PS phase (see Chapter 4) within the adopted design research methodology. The explorative identification of analogy in development process of existing enterprises indicates that analogy could be utilised non-intentionally in the design of enterprise. Therefore, it is reasonable to suggest that analogy is worth integrating into the creative design process to enhance the creativity for the design of enterprise. The research question of whether analogy exists in the development process of existing enterprises is addressed qualitatively, with data generated from the review and analysis of published speeches by successful business entrepreneurs and from semi-structured interviews of SMEs (Small and Medium Enterprises) featuring start-up companies. Elements of quantitative data analysis also help to reflect the value of analogy in the design of enterprise in this study.

Research of analogy in design mainly focuses on domains such as product design and engineering design, and analogy research mainly emerges from fields such as creative thinking and cognitive science (Kalogerakis et al., 2010). The purpose of this exploratory study is to identify research questions concerning the application of analogy in the design of enterprise, and to stimulate future research on this proposition. An attempt of analogy between a company and an automobile has been conducted in research in the business context to identify the difference between business strategy, business model and business tactics; however, more evidence is required on the existence of analogy in a business setting, and the rationale to choose key business elements to apply analogical thinking needs further clarification (Casadesus-Masanell and Ricart, 2010).

This study investigates the existence of analogy in communication activities of key people behind both large corporations and SMEs, especially start-up companies. First, public speeches by successful business leaders are reviewed and analysed, because:

1. The speakers have established a track record of innovation, entrepreneurship and business success, thus the insights from their public speeches offer credibility;

2. The chosen speakers have all contributed to enterprises which have developed into large businesses with a minimum of 250 employees, thus their opinions are relevant to the culture of development in large businesses;

3. Compared with personal interview, the data from publicly-available speeches are more accessible and comprehensive.

Second, SMEs are chosen to be interviewed to identify analogy in the development of their businesses because they are the dominant business type in the UK and account for 99.9% of the total quantity of businesses. Most of the companies being interviewed are start-up companies, which are typically micro-sized. It is important to analyse data from micro-sized companies as they account for 96% of the total quantity of businesses in the UK (see Table 7.1).

7.3.2. Identification of analogy in public speeches by influential business leaders

This study is designed to investigate the value of analogy in the realm of enterprise from a different angle. The aim is to test the hypothesis that, through the media of public communication, analogy commonly exists in the ways of thinking and expression of influential business leaders. This study reviews and analyses the public speeches by established business leaders for the identification of analogy. The value of analogy is illustrated by its consistent existence in such speeches, because otherwise no such consistent existence of analogy would be identified if it is of no value for public communication by business leaders. The positive verification of the hypothesis would lead to the conclusion that analogy is valuable for communication in the business world.

The method is to investigate whether analogy consistently exists in the entrepreneurs' arsenal for public communication and expression, in order to suggest that analogy is used to promote thinking and communication in the business realm. The analysis of speeches and the identification of analogy are conducted by the researcher himself to ensure the consistency of assessment. The researcher understands the types of analogy and has research experience in identifying and categorising analogies from text documents. Ten videos of public speeches by well-known business leaders have been selected as samples for analysis. Identified analogies are also categorised by types, which are set to include direct analogy, symbolic analogy and personal analogy, although the pattern of appearances of different types is not analysed further. Direct analogy establishes a relationship between two unlike phenomena without self-involvement; Symbolic analogy establishes a 'sign' of a phenomenon, which has as many similar characteristics as the other phenomenon. Personal analogy identifies a relationship between a person and a phenomenon which is familiar to others (Khatena, 1975).

As this is an empirical study with mainly qualitative analysis, there is no requirement for regulations on video specification, selection criteria of business leaders, or quantitative analysis of the data. It is worth noting that all the selected speeches are at formal occasions such as university commencements or high-profile business forums. Thus, it is reasonable to assume the seriousness in the attitude of business leaders towards the delivery of their speeches. The researcher analyses the video by both listening to the video and reading through the transcripts of subtitles. Any analogies identified are recorded by the researcher while listening to the speeches, then analysed and verified with the assistance of transcripts.

The analyses of the selected public speech materials involve coding the findings with protocols of identification, categorisation, and integration. To analyse each speech, the analogies emerged are to be firstly identified and recorded, then categorised according to the analogy types of direct analogy, symbolic analogy and personal analogy. In order to understand the findings qualitatively, a straightforward numerical integration is adopted for the total numbers of analogies identified. To ensure the validity of findings, each speech is analysed by both audio perception and subtitle transcripts. The findings are illustrated in Table 7.4.

Business leader	Position	Speech	Speech length	Source	Identified analogies			Total
					Direct analogy	Symbolic analogy	Personal analogy	
Elon Musk	Founder of SpaceX, PayPal, Tesla Motors &SolarCity	Commencement Speech--Caltech 2012	16'16"	https://www.youtube.com/watch?v=MxZpaJK74Y4	4	2	0	6
Mark Zuckerberg	Founder of Facebook	Commencement speech--Harvard 2017	32'35"	https://www.youtube.com/watch?v=BmYv8XGl-YU	3	2	0	5
Bill Gates	Founder of Microsoft	Commencement speech--Harvard 2007	26'25"	https://www.youtube.com/watch?v=zPx5N6Lh3sw	1	3	0	4
Steve Jobs	Founder of Apple, Pixar	Commencement Speech--Stanford 2005	14'33"	https://www.youtube.com/watch?v=D1R-jKKp3NA	6	3	1	10
Tim Cook	CEO of Apple	Commencement Speech-Tulane 2019	17'24"	https://www.youtube.com/watch?v=paqAE0p69AM	6	12	0	18
Michael Bloomberg	Founder of Bloomberg L.P.	Commencement Speech-Harvard 2014	24'10"	https://www.youtube.com/watch?v=Zhfn2zgFFJ8	2	10	0	12
Warren Buffett	CEO of Berkshire Hathaway	Speech with advice for entrepreneurs on Goldman Sachs "10000 small business summit" on 13/02/2018	20'55"	https://www.youtube.com/watch?v=P23HnJM-2kM	1	4	0	5
Jack Ma	Founder of Alibaba	Keynote speech at Gateway Canada on 25/09/2017	32'17"	https://www.youtube.com/watch?v=A5Wvy9WOxwU	4	4	0	8
Mary Barra	CEO of General Motors	Commencement speech-Kettering 2013	12'20"	https://www.youtube.com/watch?v=jOokPTtXZYQ	1	5	0	6
Jeff Bezos	Founder and CEO of Amazon	Graduation speech-Princeton 2010	12'20"	https://www.youtube.com/watch?v=vBmavNoChZc	0	3	0	3

Table 7.4. Identification of analogy from business leaders' public speeches

According to the findings, all business leaders have used analogy in their public speeches chosen for this study. The consistent existence of analogies in these speeches indicates a positive value of analogy in public communication in the business realm. Whether analogy has been intentionally utilised in the selected speeches is both hard to confirm and beyond the scope of this study. Explaining the distinct amount of analogies identified in these speeches by different business leaders is not attempted due to the limited sample size, and it is the findings that analogies are identified in all the speeches that is relevant to this study. The findings disclose that analogy is used in important public speeches by business leaders who are the key figures for exceptionally large and successful enterprises.

7.3.3. Analogy in the development of enterprises from interviews

a. Scope of study

This exploratory study attempts to identify the existence of analogy in the establishment of 16 SMEs featuring start-up companies. The cohort of selected companies are drawn from a variety of business fields for reduction of potential participant bias. The companies practice in diversified fields including: financial technology, educational technology, advanced manufacturing, healthcare and medicine, aerospace technology, IOT (Internet of Things), environmental technology, robotics, VR (Virtual Reality), Energy and AI (Artificial Intelligence). Semi-structured individual interviews are conducted with the CEO/CTO of the companies on the identification of market requirements, the development of technology and the establishment of business.

b. Research methods and implementation

This study uses the interview as the tool to obtain an understanding on the use of analogy in the development of start-up companies, which is the same research method adopted to explore the use of analogy in selected design and engineering consultants (Kalogerakis et al., 2010). The interview questions are designed around three key topics, consisting of market requirement/gap, technology and business, all of which require a prioritised focus from a start-up technology company. The questions intend to avoid basic facts such as technology itself or business development milestones, as this information already exists and is subjective. It is the more objective thinking and views that could potentially reveal more insights into whether analogy and analogical thinking were adopted by the start-up companies, either intentionally or non-intentionally, which is this research's focus. After a series of careful consideration and consultancy, bearing in mind thoroughness and unbiasedness, the final version of the questionnaire is structured as in Table 7.5.

Question focus	**Example questions**
Market requirement/gap	• What were the market requirement/gap and how were they identified? • How did your technology fulfil the market requirement/gap?
Technology	• How did your technology develop? • What were the advantages and disadvantages of your technology? • Did you experience any challenges/issues in technology development? How did you tackle them?
Business	• How did you translate the technology into business? • What are the challenges to set up and develop your business? How did you tackle them? • (Optional) How did the company grow from early stage to today's scale? • What different challenges are facing your business now compared with the early stage? How do you tackle them?
General reflections	• Did you investigate other technologies/companies' development to compare and perhaps try to learn from their experiences? If so, how useful was this tactic and what did you achieve from this? • What are your top tips/insights for start-up experiences so far?

Table 7.5. Example questions for semi-structured interviews

Along with the objective of reducing participant bias, no disclosure of research intention of analogy identification was made until the interviews were completed to avoid intentional bias in output data i.e. possibly intentional utilisation or avoidance of analogy. An explanatory survey subsequently followed the interview to discuss the possible use of analogy and analogical thinking in the design of enterprise process. The survey results were compiled as qualitative evaluation for the study of analogy's application. The data collection methods consist of note-taking and voice recording of 16 face-to-face interviews to key persons in start-up companies. The transcripts from recorded interviews were then generated and analysed by the researcher to help identify analogies that had been used by the interviewees. The consistency in findings from analyses of noted and recorded data helps reduce the coding bias.

The protocols for coding the findings for this study differentiate with the speech analyses study, in that analogies are to be identified within the areas of market, technology and business. For each one-to-one interview, the interviewee was not initially informed of the purpose of analogy identification; instead, an introduction was provided with the aim of gathering insights from the development of their businesses. This is to eliminate intentional preference or avoidance of the use of analogy to reduce participant bias. Then, questions were asked, as shown in Table 6.5, to explore the insights from the interviewees on business experience. Notes were taken for all interviews and analogies identified were highlighted. Voice recording was utilised through a dedicated smartphone application, and the recordings were later transcribed for analysis and verification of notes. A typical interview lasted approximately 15 minutes, and was followed by a post-interview survey, during which identification of analogy was discussed and feedback was collected.

c. Research findings

Analogies have been identified in the majority of interviews conducted, and also exist in interviewees' answers to questions of all three preselected categories. It is difficult to generalise the patterns of analogy's existence from data sample of such a small size, but there are four interviews with over ten analogies identified, which could again show the value of analogy recognised in information transforming process in the setting of enterprise. A note example for the interviewing is illustrated in Figure 7.8.

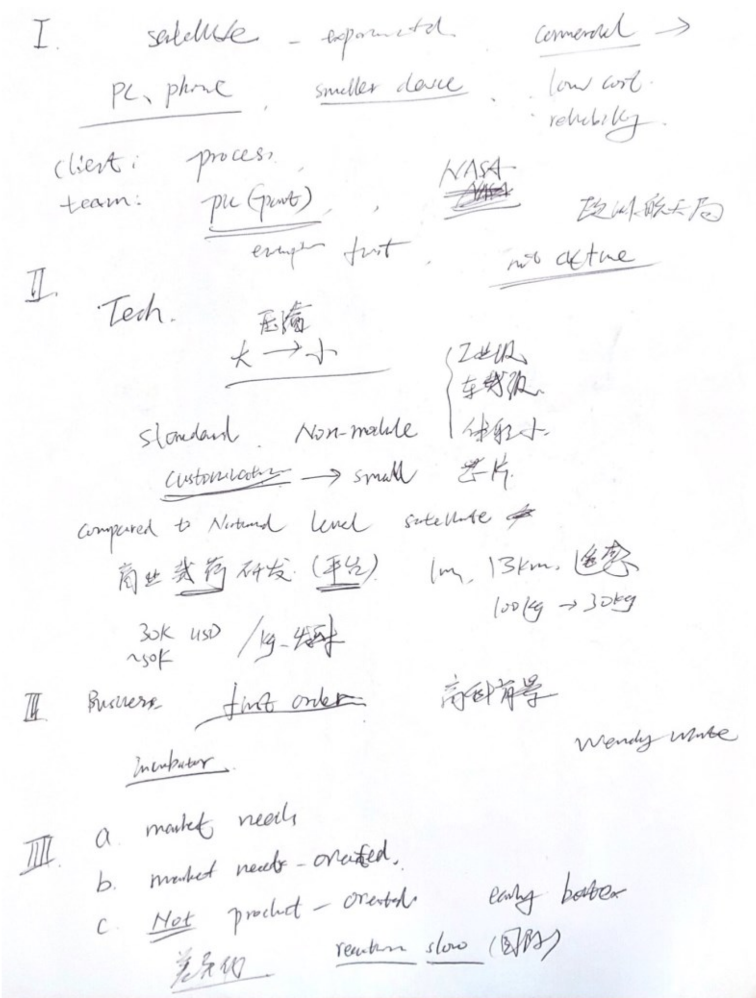


Figure 7.8. An example note from the interviews

Given the study's objective and the limited data source, qualitative observation is primarily used to interpret the findings. Comment examples from the interviewees on identification of market needs with analogy include: "…my friend suggested it would be really cool (if) there was this **death watch**, the watch that counts down to your death…"; "…In the fields such as smart city, …the attention and resources could have **overflowed like a flood**, especially at project level…" Comment examples on technology development involving analogy include: "…we spent a lot time deciding about how for the consumers we are able to **insulate them** from the regular **noises** of other smart watches…"; "…if you are willing to accept that actually you can **stand on the shoulders of the giants**, and you look around for those **giants** and you notice that…"; "…The activities in battery research then **exploded like a bomb**, leading to the disruptive development of energy sector…". Comment examples on business development containing analogy include: "…it taught us what **matrix** we should focus on in terms of running Facebook ads, adverts, reddit ads for example…"; "…how to essentially build a followership what's known as a **'tribe'** essentially of people who are all aligning towards a certain goal in terms of they are all looking to improve the way they manage their time…"; "…we had to invest in the **ticket** through learning into the **alleyway** of this field…". The key words of analogy are highlighted to mark the use of analogical thinking in these conversations in the setting of enterprise. Further original data is illustrated in Appendix 6 in detail with clear consent from the companies in line with the research ethics that this study has applied. The results from transcript and analysis are recorded in Table 7.6.

Company	Sector	Since	Analogy in Market Requirement	Analogy in Technology	Analogy in Business Development	Total No. of Analogies
A	Smart manufacture	2017	4	1	0	**5**
B	Financial technology	2016	0	4	0	**4**
C	Environmental technology	2012	0	0	0	**0**
D	Virtual reality	2017	1	0	1	**2**
E	Education	2016	4	4	4	**12**
F	Intelligent device	2018	4	5	10	**19**
G	Medical technology	2016	3	1	1	**5**
H	Mother & baby	2015	2	1	0	**3**
I	Artificial intelligence	2017	0	2	0	**2**
J	Aerospace	2015	3	1	3	**7**
K	New energy	2017	2	5	3	**10**
L	3D printing	2016	4	1	1	**6**
M	Artificial intelligence	2016	0	3	2	**5**
N	Medical device	2016	3	2	7	**12**
O	Machine vision	2016	4	1	0	**5**
P	Educational technology	2015	0	0	2	**2**

Table 7.6. Results indicating the existence of analogy from interviews

All interviews were followed by an informal survey, where the interviewee was informed of the study objective for the identification of analogy and asked to provide feedback. The majority of interviewees had no deliberate intention to utilise analogy during the interview, and were surprised to see that analogies were used non-intentionally. All interviewees commented positively on the value of analogy in enterprise settings and expressed the interest in adopting analogy in future business-related activities. This recognition and acceptance of analogy, along with findings on the existence of analogy, support the argument that the use of analogy has the potential to enhance enterprise in areas such as the identification of market requirements, and the development of technology and business.

7.3.4. Analogy-empowered creative design process for the design of enterprise

It is reasonable to argue that an analogy-empowered creative design process enhances the design of enterprise, as previous findings have established:

1. A possible model for creative design process (Section 7.2);
2. Analogy consistently exists in ways of thinking and activities in the realm of enterprise (Section 7.3);
3. Creativity benefits from analogy (Sections 3.6 and 6.4).

With the integration of valuable elements from the review of design processes including divergent-convergent thinking, human-centred element and comprehensiveness of design, a possible process for the design of enterprise featuring analogy can be adapted, as illustrated in Figure 7.9.

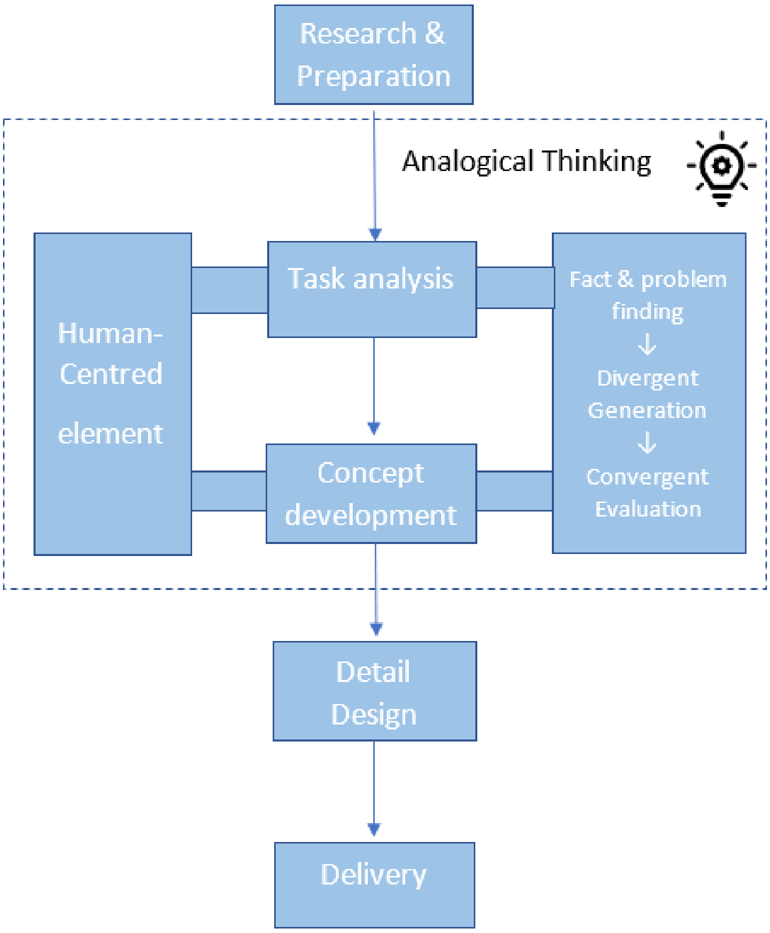


Figure 7.9. A possible process for analogy-empowered design process of enterprise

The suggested design process for enterprise described here essentially views an enterprise as a design object and the outcome of a series of design activities. The design process forms a core part of the design of enterprise, the whole canvas for which involves richer planning and more thorough implementation. The research purpose so far not only reviews creativity, analogy and the process of enterprise design, but identifies the interconnected relation between them, and also recognises the relation by suggesting the analogy-empowered creative design process for the design of enterprise. The identification of analogies in business leaders' public speeches and the interviews with SMEs qualitatively evaluates the validity of integration of analogy in the design process of enterprise. Further practical evaluation in Chapter 8 will investigate whether the findings are applicable to the real-world design tasks of enterprise.

7.4. Conclusions and discussions

This chapter strategically reviews the interrelations between creativity, analogy and design of enterprise, as well as well-established design processes, so that it builds up to the validity of proposing an integrated creative design process featuring divergent-convergent thinking and human-centred element. Empirical studies are conducted to identify existence of analogy in activities of enterprise settings including large corporates and SMEs. The findings indicate that it is reasonable to integrate analogical thinking into the process and propose an analogy-empowered creative design process for enterprise. The new elements of contribution to the existing research of creative design process consist of not only the proposed integration of analogical thinking into the creative design process, but also the novel suggestions to include human-centred element and divergent-convergent thinking. As a result, the analogy-empowered creative design process is presented as a theoretical framework of guidance to enhance design. These new insights are the outcome of the Prescriptive Study phase, which is based on the elaboration of existing research on creative design process, and supported by the logical reasoning.

The establishment of the process follows a clear rationale built on the findings from previous chapters with evolving steps: 1) identify the value of analogy in creativity through the review of creativity, creativity tools, creative processes and analogy, resulting in the suggested realisation of analogy's value in creativity with the Analogical Creative Process (ACP) (see Chapters 2 and 3); 2) consolidate a positive correlation between analogical thinking and design through the findings from a real-world engineering design project, with supplementary support from literature evidence and evaluation (see Chapter 6); 3) propose an integrated creative design process based on the review of the essence of common design processes and reasonable assumption of a possible integration of creative process and design process, the idea of which is echoed by existing research (Howard et al., 2008).

The proposal of an analogy-empowered creative design process also aims to tackle the issue identified earlier that the potential of systematic application of analogy in creative design are inadequately explored. Such potential is highly possible as the existence of analogy has been identified in business leaders' public speeches and the researcher's interviews with SMEs. The proposed systematic analogical process forms an essential role in the design of sustainable enterprise, the essence of which will be initially evaluated in Chapter 8 for its applicability and effectiveness.

Chapter 8. Application of the analogy-empowered creative design process for enterprise design in a case study

This Chapter further evaluates the findings of the analogy-empowered creative design process from Chapter 7, by applying the process in a real-world enterprise design project. The Softs Systems Methodology is adopted to guide the action research activities to ensure the research's rigour and comprehensiveness. Insights into the application of analogical thinking in enterprise design are gathered throughout this case study, along with the analysis of business elements including sustainable development, the pathway to impact and risk management. The initial outcome of the case study is also reported with an achieved early-stage business milestone.

8.1. Introduction and methodology

According to the chosen overall research methodology DRM, this chapter's purpose is to evaluate the proposed design support developed in the Prescriptive Study (PS) phase. The Initial DS-II is undertaken to evaluate the support developed by PS stage, with aim of indicating the applicability, usability, usefulness and expected success of the proposed analogical process. Short of actually creating a start-up company, this case study would be purely theoretical and may lack support from real-life evidence. Previous chapters have investigated the application of analogy in theory in the design of an enterprise. This case study will discover whether analogical thinking embedded creative design process is applicable in the design of enterprise.

The evaluation is undertaken via application in a case study of real-world enterprise design project, which involves setting up a start-up company offering customised lubrication solutions. The chapter's hypothesis is that the enterprise design activity and outcome are able to benefit from the utilisation of the proposed analogy-empowered creative design process, and that there is positive correlation between utilisation of analogical thinking and the design outcome. This chapter carries out an application evaluation for the proposed design process and attempts to show that the process involving analogical thinking can be successfully applied to the real-world enterprise design project and an outcome is possible. The longer-term development of the start-up company will need to be monitored and evaluated by follow-up studies.

The enterprise design activity involves the researcher as a participatory stakeholder of the research and action, to investigate an ill-defined design problem in a social and business environment. The case study is to evaluate the analogy-empowered creative design process for enterprise design, which essentially features analogical thinking, following the systematic guidance of Soft Systems Methodology (SSM). SSM has been identified as suitable to guide the evaluation of analogical thinking in this case study. SSM is valuable in dealing with systems with "soft factors" such as human perspectives and activities, ever-developing situations, instead of the "hard" problems with clear definition on challenges and goals (Wang et al., 2015). It is evident that the possible process suggested in Figure 8.1 has overlapping steps with SSM on understanding the design task (step 1 and 2 in SSM), Detail design and delivery (step 6 and 7 in SSM). The reasons are twofold: 1) Both methods require understanding and knowledge of the situation and task to ensure application success; 2) The analogy-empowered creative design process of enterprise does not need a rigid form to perform, instead flexible comprehension and application should act as less of an obstacle as long as analogical thinking is applied and the key elements are achieved. Similarly, although SSM does have a clear process structure, the practitioner should use it in an adaptive and flexible fashion suitable for the practice (UMSL, 2015).

With the help of SSM in clarification of design tasks, analogical thinking within the creative design process for enterprise is expected to focus on the conceptual design ideation of the enterprise in question. The clear step-by-step process of SSM distinguishes between the system thinking world and the real world so that potential improvements are possible, as illustrated in Figure 8.1.

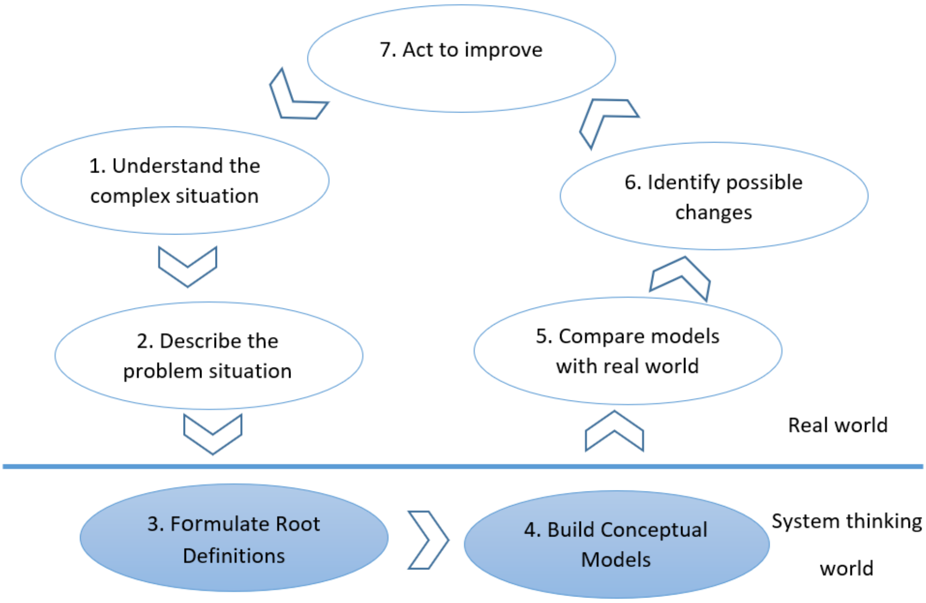


Figure 8.1. The seven-step process of SSM

8.2. Case study under SSM framework

8.2.1. Understanding of the complex situation and description of the problem

The starting point of SSM is to obtain an in-depth understanding of the complex real-world situation facing the enterprise designer. The problematic situation indicates the scope of improvement. The outcome of this phase echoes the traditional market analysis and identification of challenges and needs under the context of business.

After more than 150 years of development of modern industry, the principles of the lubrication science have become well-established, with extensive of industrial experience. The industry has been relatively conservative in the sense that many existing formulas of lubricant have been used as solutions for decades, but without significant change. A series of interviews of the lubrication researchers and industrial practitioners reveal that there is not much drive for change as the technology has matured for a long time and continues to work well. Furthermore, the power of existing industry main players has been so strong that new technologies can be easily silenced or bought off, with means of technology dominance and or financial superiority.

The essential principle of lubrication remains unchanged through the modern era of development. A typical lubricant is formed principally of two components: the base fluid (approximately 95% of the volume) and chemical additives (approximately 5% of the volume) that are dissolved or dispersed within the base. Base fluid, be it extracted from mineral oil or synthetically produced, normally determines the primary properties such as thickness, coolant, range of working temperature, environmental impacts and additive compatibilities. Additives, despite only taking up a small percentage of volume, would impact a series of properties of lubricant, including dispersant, detergent, extreme pressure additive, viscosity index improver, oxidation inhibitor, corrosion inhibitor, antifoaming agent, anti-wear and scuffing agents, etc. Therefore, it would be important, from a technological point of view, to understand the functions and properties of chemical additives, as well as to adjust the types and number of additives according to the given working conditions.

Currently, the industry often uses standard lubrication oils or greases available on the market, which can provide a considerable level of lubrication. However, when it comes to the science of lubrication, no standard solutions fit all working conditions and requirements perfectly. Due to the lack of knowledge or awareness, or perhaps even budget restrictions, industrial practitioners tend to settle down with what standard lubrication oils can offer. As a result, the performance of machines is comprised, the needs for repair increase and the lifespan of equipment is shortened. Moreover, the cost of such standard lubrication solutions can be higher than necessary. The design problem can be therefore described as follows: Industrial practitioners lack access to the most technically suitable lubrication solution which is cost effective.

The start-up company as the enterprise design outcome in this study will be referred to as “the Company” for consistency. The Company has gained general understanding of Chinese lubricant market; therefore, the Chinese market is seen as starting point for the Company. By 2016, there were over 2000 providers for lubricants in China, which was approximately half of the total counts of worldwide lubricants manufactures; however, the top-end market in China has been dominated by the imported brands (Ma, 2016). The current market shares of lubricants in China is illustrated in Table 8.1 (Wu, 2019). The total consumption of lubricants in China reached 6,416 thousand tons and is expected to increase by approximately 4.6% each year (CIConsulting, 2018). The applications of the lubricants reflect the level of economic growth, the improved understanding of the manufacturing facilities and the increased level of awareness of environmental protection. Therefore, advancement of lubrication technology should aim for not only improved formula and technical performance, but also increased level of environment friendliness (Wu, 2019).

Enterprise category	Market share	Primary targeted market	Representative enterprises
International provider	Approximately 25%	Top-end passenger cars	ExxonMobil, Shell, BP, Fuchs
State-owned company	Approximately 50%	Overall applications	Kunlun, Sinopec lubricant
Privately owned company	Approximately 25%	Special vehicles	Yuchai Group, Sure energy

Table 8.1. Current market shares of lubricants in China

8.2.2. Formulation of Root Definitions of relevant systems

The formulation of Root Definitions is a key phase of SSM, and indicates the scope of thinking from the real-world situations to the system thinking domains (Williams, 2005). The Root Definitions involve clear definitions of the purposeful activities as a transformation process, the elements of which should consist of the content of the mnemonic CATWOE (Checkland, 2000).

Application of PQR into the existing situation for this case study would lead to a possible version of the Root Definitions as: "The Company with feasible business structure addresses the identified market needs by means of technological advancement." The Root Definitions under CATWOE framework for this case study should involve the following elaboration.

a. Customer: The clients who are seeking for improved and more cost-effective lubrication solutions for their needs and are willing to be the Company's customers.

Industries such as manufacturing, motoring and machinery have needs for optimised lubrication solutions to improve performance, increase working lifespan, and reduce maintenance cost. The application of existing lubrication solutions fulfils the industrial needs to an extent but not perfectly. These customers are all potential customers of the Company, as the Company is determined to raise the customers' awareness of lubrication, create improved lubrication solutions for customers with needs of technology advancement, and develop more cost-effective lubrication solutions.

b. Actor: The researcher and key members of the Company, who will conduct activities to facilitate the transformation for both research and business purposes.

This case study as Action Research serves the dual purpose of research and action. The researcher and business partner form the key members of the Company, with an in-depth understanding and practical experience in tribology science and the lubrication technology. The team have access to leading laboratory facilities to conduct research activities including experiments and bench testing.

c. Transformation

The route to the market is of concern and the process of change from input of technology-led lubrication technology to the output of lubrication solutions, including product and service, with commercial value. In addition, the transformation is expected as the outcome of this case study from random business ideas to a more structured model for business development.

d. Weltanschauung (World views): the added value of the research and commercial activities undertaken by the Company as well as the wider impacts the activities may cause.

The Company, as the intended industry disrupter, aims not only for the gain of profit by providing products and services, but also the increased pressure to the lubrication solution providers for improved solutions with better value for money. The added value and wider impacts need to be analysed and attempted through the transformation.

e. Owner: The Company

The Company is solely responsible for the creation of the business entity, the offering of the compatible products and services, and the continuous response to the need for improvement.

f. Environment: The key external constraints that have significant influence on the Company's performance in both research and business contexts.

The Company will need to consider the key external constraints and restrictions to achieve goals in the most efficient manner possible. This is particularly essential for a start-up company in the context of fierce business competition. Some of the external constraints contribute to shaping the business model and strategy of the Company.

8.2.3. Build Conceptual Models

The establishment of the Conceptual Models is the second step within the system thinking domain. The Conceptual Models form a logic view of the transformation of the system based on the analyses through CATWOE framework. For this case study, a possible set of Conceptual Models is illustrated in Figure 8.2. It is worth noting that the arrows indicate dependency i.e. subsequent steps are dependent on previous steps and rely on the output of previous steps.

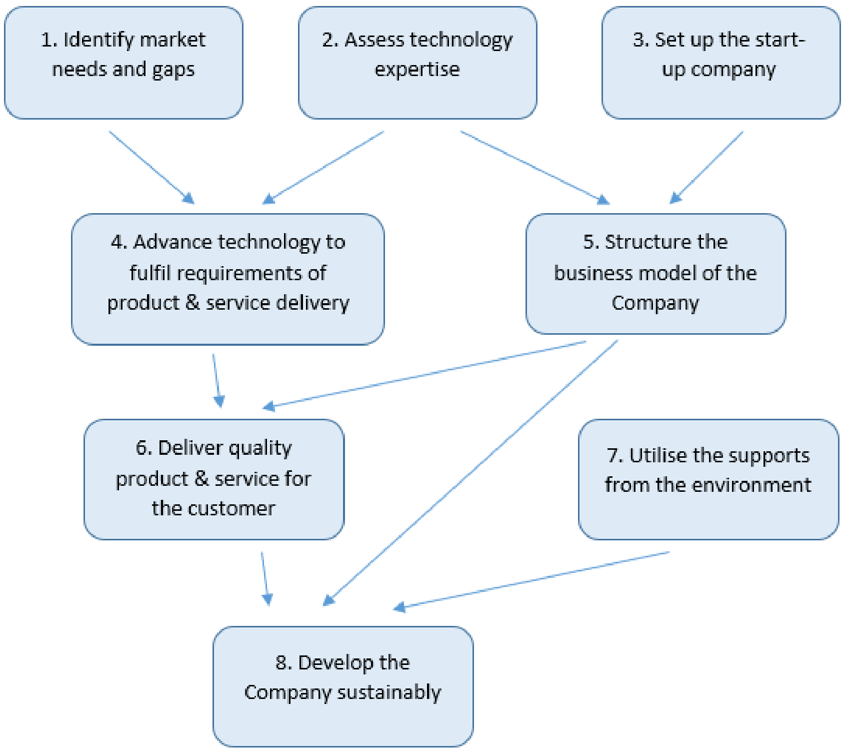


Figure 8.2. A possible set of Conceptual Models

8.2.4. Compare models to real world to achieve changes

This phase indicates the returning of activities from system thinking domain back to the real world. For this case study, a comparison is illustrated in Table 8.2. with suggested possible actions. Additionally, generalised entries for the Conceptual Models are included in the comparison to form a fuller picture, such as the monitoring of the management and operations of the Company and risk management.

Conceptual Model	Real-world situation	Possible action
1. Identify market needs and gaps	Basic understandings of the market situation have been obtained by reviews and interviews.	1. Identify and elaborate on specific market needs and gaps.
2. Assess technology expertise	Knowledge of technological insights are gathered from scientific research.	2. Review and understand clearer technology advantages.
3. Set up the start-up company	Business ideas are clearly expressed.	3. Set up the basic structure of the Company.
4. Advance technology to fulfil requirements of product & service delivery	Only general technology insights are available.	4. Decide the direction and target for technology development.
5. Structure the business model of the Company	Only thoughts on aspects of business model exists.	5. Shape and decide the Company's business model.
6. Deliver quality product & service to the customer	No delivery has happened yet.	6. Achieve an outcome from previous actions aiming for the first delivery.

7. Utilise supports from the environment	Policy support and investment interests are available.	7. Adjust business model to allow external support to benefit the Company.
8. Develop the Company sustainably	Too early a stage to be applicable.	8. Monitor on-going development of the Company.
9. Monitor Company management and operations	Too early a stage to be applied rigorously.	9. Discuss regularly within the Company for necessary adjustments.
10. Manage risks	Initial assessment of risks carried out.	10. Manage risks as the Company grows.

Table 8.2. Comparison between Conceptual Models and real-world situations

A selection of possible actions is generated as the result of the comparison of logic Conceptual Models and the existing real-world situations. Even though the possible actions are derived from rigorous analysis and are all necessary to implement, further evaluation of the actions are needed. Some key possible actions are necessary to be conducted first because the other actions are dependent on the outcome of these actions. Furthermore, as a start-up enterprise, the Company has finite resources to take all possible actions, thus prioritising the evaluation of possible actions is required.

Figure 8.3 (Burge, 2015) shows a possible evaluation outcome in order to prioritise the possible actions undertaken using the Ease Benefit Matrix. A two-dimensional space is created by measurements of benefit and ease of the possible actions, and all identified possible actions are located in the space. The scale of the actions indicates the resources required for conduction. All indicative locations of the possible actions have been determined collectively by the key members of the Company. For instance, possible action 5 (Shape and decide the Company's business model) is considered to benefit the Company significantly, requires a considerable amount of resources and could be difficult to achieve.

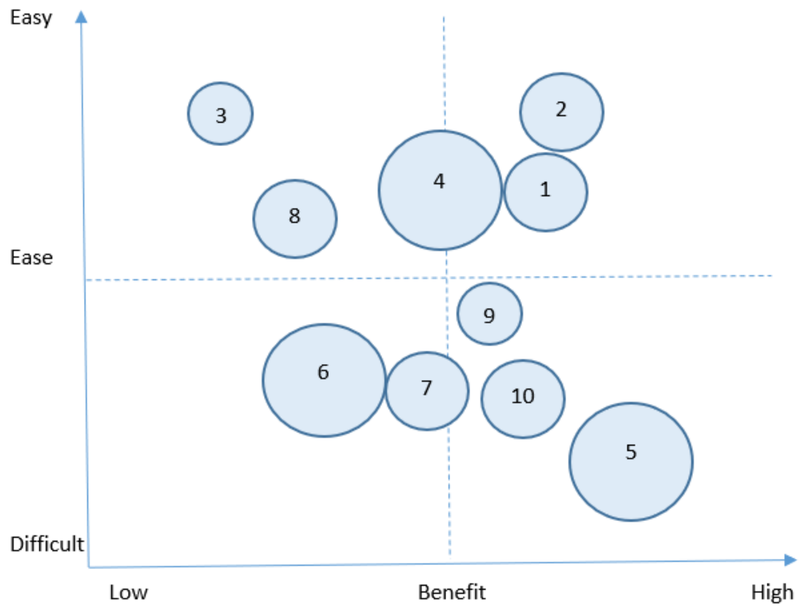


Figure 8.3. Ease Benefit Matrix of possible actions

The analysis with the Ease Benefit Matrix implies that prioritised attention should be diverted to three key elements of the Company's sustainable development, with associated actions required. These elements are understanding the market needs and gaps, the advancement of technology and the decision on the Company's business model. The conceptual design within the proposed analogy-empowered creative design process (See Table 8.7.) of possible solutions to the tasks representing these three key elements are undertaken with the assistance of analogical thinking. The key elements of the proposed analogy-empowered creative design process for enterprise are embedded in this phase for the design task of conceptual idea generation.

8.3. Search for design solutions to key elements using analogical thinking

8.3.1. Understanding of the market needs and gaps

Comprehensive understanding of the market needs and clear identification of the market gaps are required to shape the direction of the Company's technology and business model. To intentionally apply analogical thinking, source domains need to be identified. This is achieved based on the researcher's knowledge and experience of a domain to decide if it is applicable. Just as analogies can be formed from different source domains, the solution is non-unique. For this search, the domain of fashion is selected as the source domain to establish possible analogies for this task. To identify the market requirements in this case study, ACP has been applied to enable the searching for understanding and analogical mapping as illustrated in Figure 8.4.

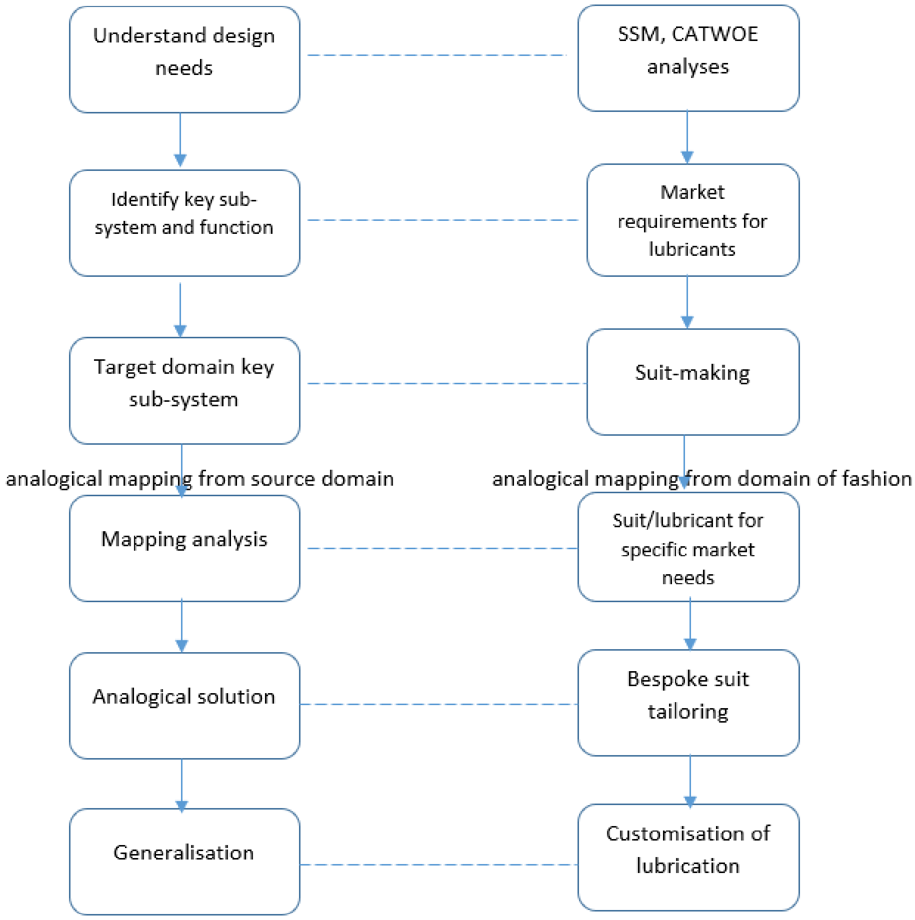


Figure 8.4. ACP enabling understanding of market requirement

In accordance with the essence of ACP for analogical thinking, the primary relationship between precision tailoring and unique body measurements within the domain of fashion has been analogically mapped over to the domain of engineering, leading to the suggestion of the market's need for customised lubrication. The problem-driven analogical thinking is adopted, and an analogical mapping is established between the customisation of lubricant solutions and bespoke suit in fashion, at both the characteristic and relational level as described in Table 8.3.

Analogy	Customisation of lubricant solutions	Bespoke suit tailoring
Domains	Engineering	Fashion
Characteristics	Supply of generic lubricants to specific industrial working conditions	Supply of tailored suits to different body shapes
Relations	Mismatch between specific needs and supply of generic solutions	Tailored suits uniquely made according to body measurements
Mapping on characteristics	From bespoke-made suits to customisation of lubricant solutions	
Mapping on relations	From meeting customised requirements in suit-making to meeting customised requirements in industrial lubricant solutions	

Table 8.3. Analogical mapping between customisation of lubricants and bespoke suit tailoring

At the characteristic and relational level, customisation or bespoke according to individual requirements is the key mapping strategy. As previously discussed, an effective analogy would derive from a powerful mapping process that reflects the top qualities transferred over between two distant domains. There are other less significant characteristics and relations in both the source and target domains, which should be deliberately ignored when the mapping is established, as they may bring in distraction for mapping and decrease the effectiveness of analogy.

The customisation of lubrication solution is limited to product supply but can include further services to ensure product performance and customer satisfaction. Table 8.3. aims to only reflect the mapping of key relations from fashion as source domain and engineering as the target domain. The strength of analogical thinking in this case enhances further development of this case study in identification of market gap. For instance, bespoke suit making often involves services in addition to body measurements and the making of the suit; a customer would also have the opportunity to communicate with the tailor about their lifestyle, preferences as well as to receive follow-up alteration and after-sale customer care. Similarly, this type of customer service can also be transferred to lubricant-supply business. On top of full customisation of lubrication solutions based on pre-assessment of customers' expected working conditions, the Company offers follow-up monitoring and evaluation of lubricant performance as well as lubrication consultancy. The aim is to provide clients with not only most suitable bespoke lubrication solutions, but also a full package of services to enhance customer experience. In other words, the start-up's unique selling point is full customisation, covering both products and services. As indicated earlier from interview feedback, some customers lack an in-depth understanding of the science of lubrication and opt for the standard solutions available in the market; some customers are aware of the importance of suitable lubrication but are unconcerned with the potentially extended life time of operation, simply because as manufactures they are only required to provide limited warranty for their products; other customers have to compromise and settle down for basic lubrication solutions due to the restriction on cost. It is expected that the delivery of this fuller than usual service would contribute to the accurate identification of market gap, and therefore lead to larger chances of business success. The outcome of identification of market gap and creation of enhanced business model as a result of analogical thinking is illustrated in Figure 8.5.

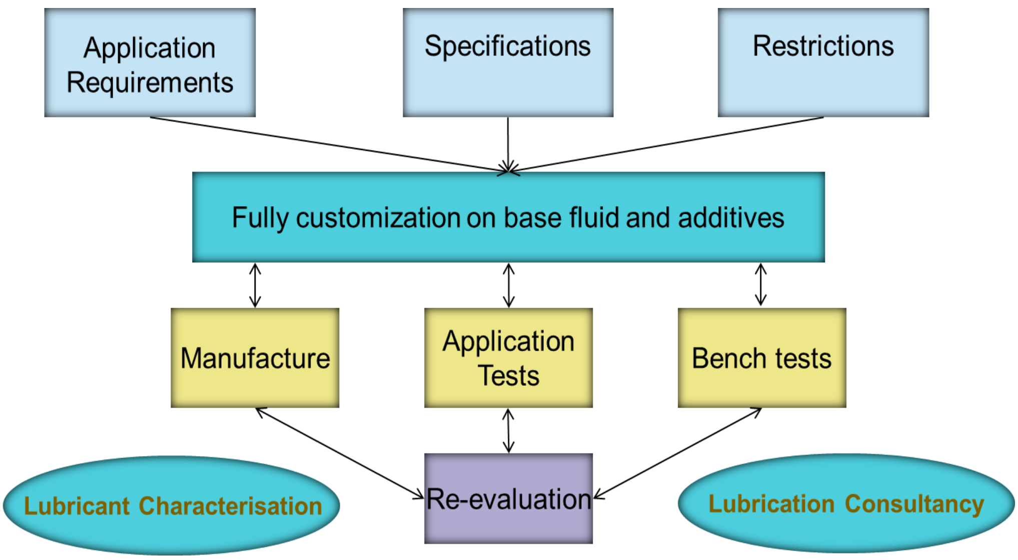


Figure 8.5. Identified market gap and proposed solutions

8.3.2. Advancement of the Company's technology

A major challenge facing all technology start-ups is their development of technology and applications. The Company has faith in the viability of its technology but, given the conservative characteristics of the mechanical engineering industry as well as competition from the well-established global competitors, it would mark all the importance in how to decide to develop its technology for applications. The Company intended to apply analogical thinking in understanding properties and technical functions of typical additives for lubricants as a deliverable task within the conceptual design phase. A preliminary investigation of the primary technical properties of the additive in question are shown in Table 8.4.

Additives	Properties and Technical Functions
Oxidation Inhibitors	Inhibit oxidation, prolong useful life of lubricants
Corrosion Inhibitors	Form an impervious reaction film to reduce chemical attacks
Rust Inhibitors	Adsorbed on metal surface to reduce water mobility to limit electrolytic attack by oxygen and water
Friction Modifiers	Reduce friction coefficient
Anti-wear Additives	Reduce wear in thin film at high temperatures
Extreme Pressure Additives	Prevent scuffing under extreme working conditions (e.g. high pressure, high speed)
Detergents	Prevent varnish from building up
Dispersants	Prevent coagulation of micro-scale carbon particles
Viscosity Index Improvers	Increase viscosity index
Pour point Depressants	Reduce forming of large wax crystals

Foam Inhibitors	Prevent foam from building up and circulating into bearings and gears
Dyes	Improve lubricant colour
Odour Improvers	Improve lubricant odour

Table 8.4. Primary technical properties of additives in question

All additives from Table 8.4 work at micro-scale level to improve the properties and functions of lubricants. Therefore, to integrate analogical thinking into the idea generation, the analogical creativity tool Smart Little Persons (SLP) has been adopted to better understand how the different additives function (see Section 3.4.1). The key of SLP is to create smart tiny beings by imagination, where elements from both personal and fantasy analogy exist. The additives are imagined as being formed by extremely large numbers of smart little beings, and with personality and sense of task, they will work together to achieve specific functions allocated for them at micro-scale. For instance, to break the connections between air molecules to prevent forming of air film (form inhibitors); to form an impervious layer of reaction film to reduce chemical attacks (corrosion inhibitors); and to immobilise water molecules so that rust is reduced (Rust inhibitors). With the assistance of analogical SLP, a selection of seven typical lubricants and their properties are recommended, as the initially representing products offered by the Company (Figure 8.6).

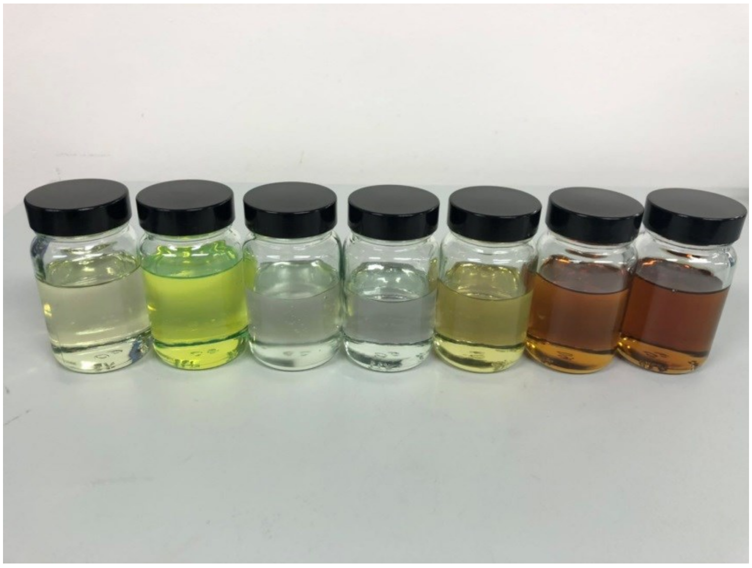
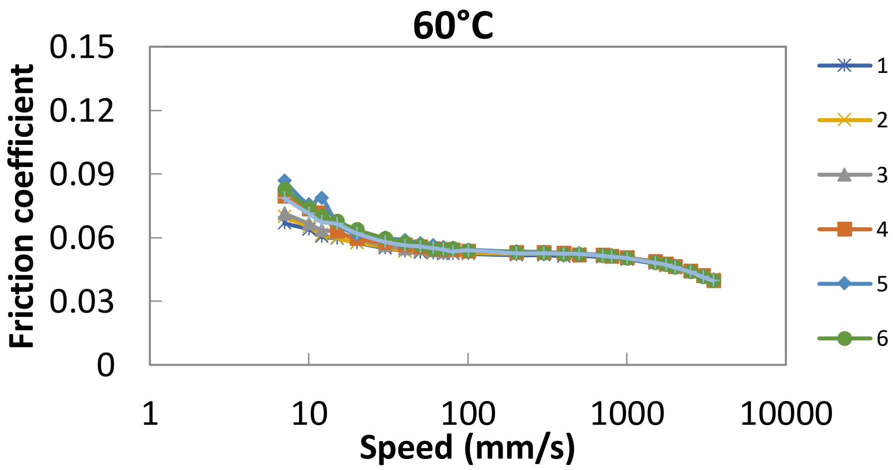


Figure 8.6. Illustration of seven bespoke lubricants

The effective use of SLP in this area should enhance the understanding and perception of how additives work fundamentally, thus revealing more insights into how to improve the technical functions of additives through more precise formula and technical adjustments. In addition to technology advancement, it has been noticed that the analogy also helps more effective communication of technical issues between the colleagues with and without the technical background of lubrication technology. Analogical thinking, in the form of personal fantasy analogy of SLP, helps understand the characteristics and functions of the additives and achieve creative ideation accordingly.

Thanks to the analogical thinking with SLP, the Company is able to understand the key functions of additives and therefore focus on the development of lubricants, of which the friction coefficients vary according to the specific working conditions. Representative differences of the friction coefficients along with change of speed of relative movement between the selected 7 (or 6 as appropriate) sample oils are illustrated under variable conditions of temperature and pressure in Figure 8.7 and Figure 8.8, respectively.



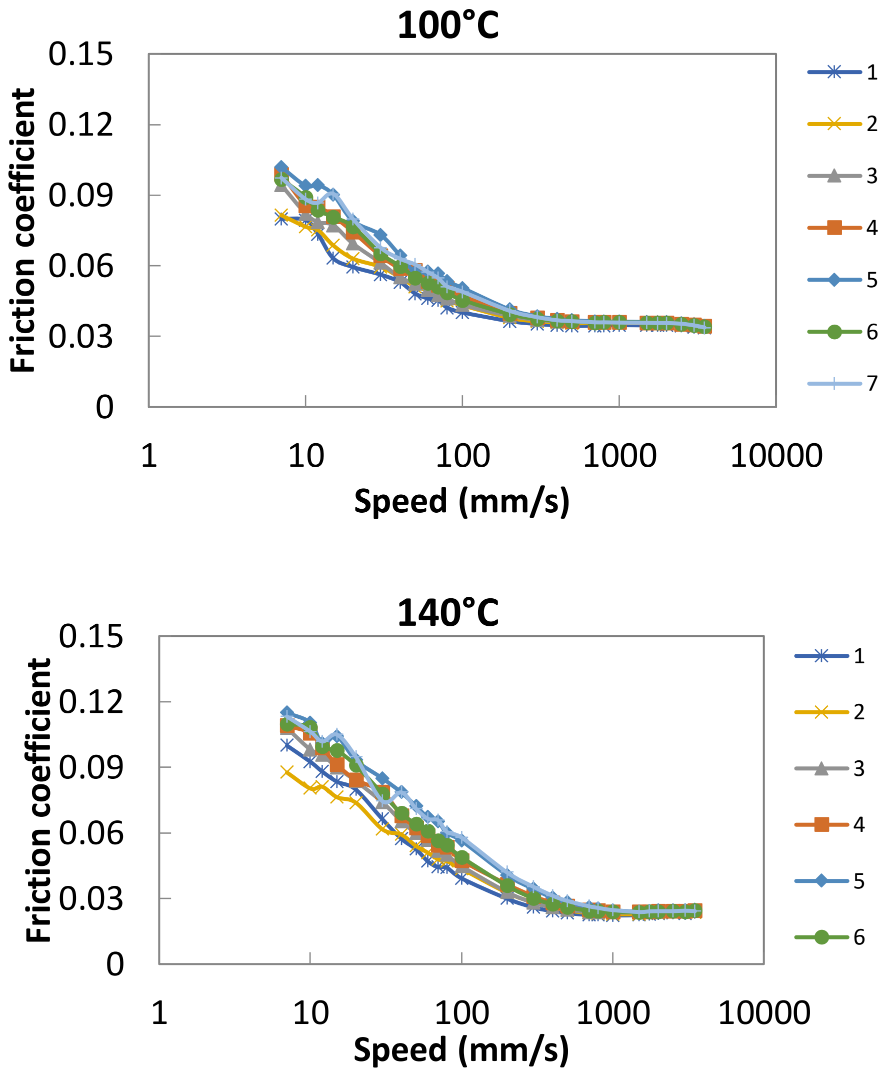
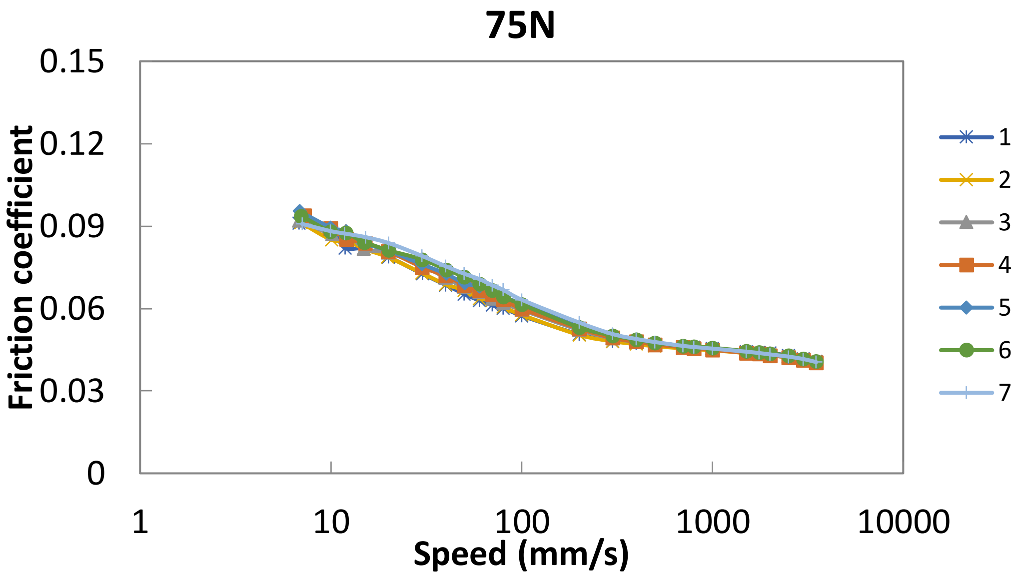
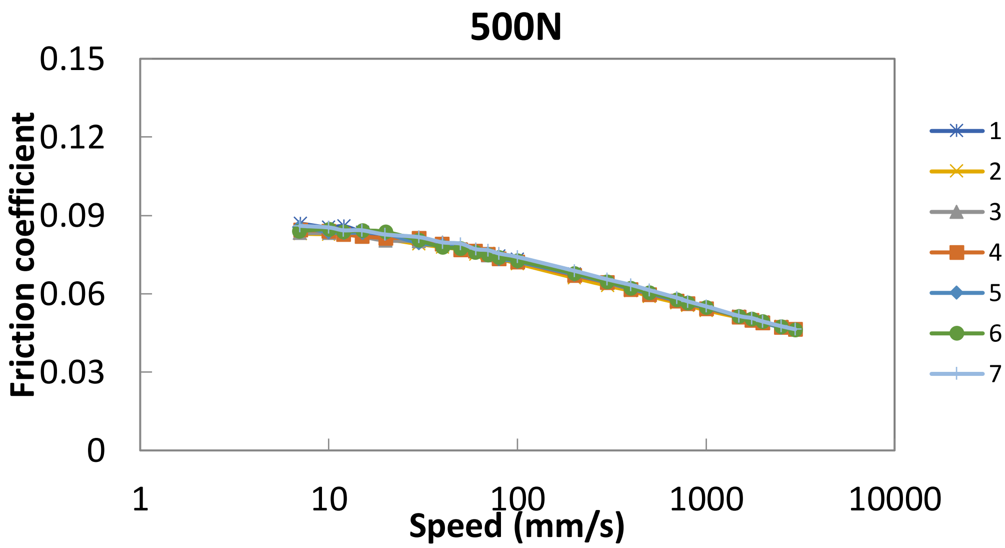


Figure 8.7. Friction coefficients of the selected oils under different working temperature


75N
Friction coefficient
0.15
0.12
0.09
0.06
0.03
0
1
10
100
1000
10000
Speed (mm/s)
1
2
3
4
5
6
7


500N
Friction coefficient
0.15
0.12
0.09
0.06
0.03
0
1
10
100
1000
10000
Speed (mm/s)
1
2
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7

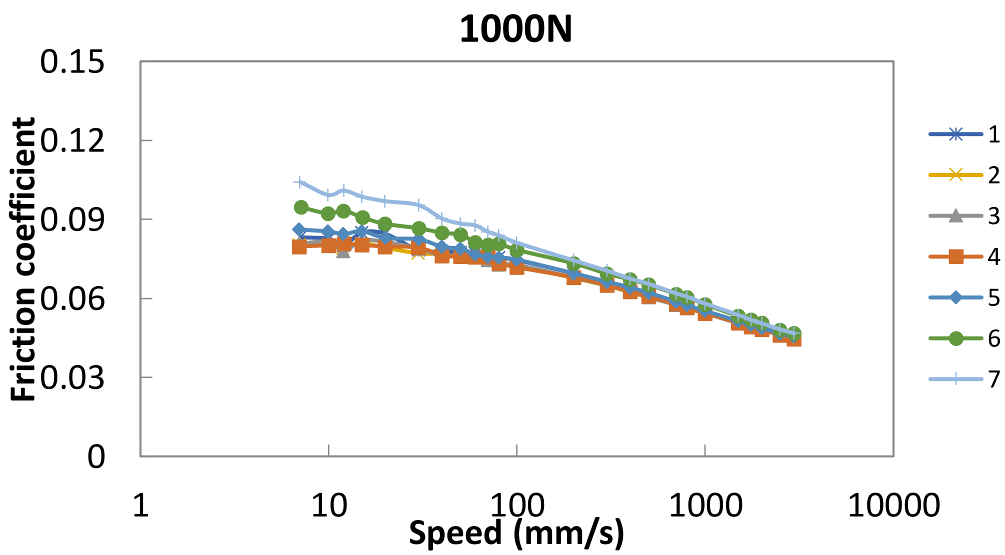
1000N
Friction coefficient
0.15
0.12
0.09
0.06
0.03
0
1
10
100
1000
10000
Speed (mm/s)
1
2
3
4
5
6
7

Figure 8.8. Friction coefficients of the selected oils under different working pressure

A selection of possible lubrication products is proposed based on the analyses of the technical properties of the lubricates, primarily on the friction coefficient as the main lubricating factor. The selection of lubrication solutions includes engine oil, aircraft gas turbine oil, hydraulic fluid, multipurpose automobile oil, industrial gear oil, and transmission oil. More details on these solutions are reported in Appendix 7.

8.3.3. Decision on the Company's business model

In addition to the identification of market requirements/gap and the development of key technologies, the establishment of the business model for the Company as a start-up also requires much attention and input. The business model will need to exploit all the resources that the Company has in technologies and values, and also be sustainable and feasible. It is extremely difficult to attempt to copy other businesses' growth path exactly, thus the Company will need to design its own business model to fulfil its own needs.

Analogical thinking has been adopted in the design of business model and a feasible solution could be a morphological and functional structure inspired by trees in nature. Table 8.5 below shows the analogical mapping of characteristics and relations between the source domain of nature and the target domain of business, following the essence of ACP guideline.

Analogy	Tree	Business model
Domains	Nature	Business/Enterprise
Characteristics Mapping-Morphology	Trunk, branches, sub-branches	Core technologies, products and services, extended products and services
Relations Mapping--Function	Branches and sub-branches grow to harness more energy, which in return feeds the tree's growth as a cycle	The company sets up divisions of products/services for further development of the entire business

Relations Mapping- Time	Only the healthiest branches grow first, which ensures the tree's sustainable growth; at later stages, the tree will have enough resources to bloom	Business strategy must be focused on the core development at early stage of the start-up; after the expansion of the company, more attentions could be extended to diversified directions for development

Table 8.5. Analogical mapping between domains in business model development

With the conclusions derived from the analogical thinking, the business development model of the Company has been decided as illustrated in Figure 8.9. The discussions on ACP have concluded that analogical mappings at higher levels tend to lead to more valuable and inspirational solutions, and the mapping of characteristics does not have to be reflected in the solutions as a lower-level mapping. For instance, although the morphological and functional characteristics and relations are mapped over between the domains of nature and enterprise, the solution of business development model does not have to be presented in the shape of a tree.

Figure 8.9. Functional structure for the Company business model

The Company' business development model always acknowledges lubrication solutions and technologies as the core of business development. At the early development stage, any feasible strategies should consider bespoke lubricants and functionalised additives as product deliverables, the consultancy on lubrication and design as service deliverables, while the quality control of products, services, and customer care as collateral efforts to contribute to the sustainable development of the Company.

8.4. Sustainable development of the Company

8.4.1. Route to sustainable development

Thanks to the power of analogical thinking on three key aspects in this case study, the development outline of the Company has become clearer. Analogical thinking, as mentioned above, has enhanced creative ideation and decision making, and the outcome of analogical thinking has been practical. As a complex project of designing a start-up Company, all key factors in product, service, research and business development need continuous monitoring. The value of analogical thinking in this case study is not limited to solution finding, but also extends to a novel way of thinking where creative ideation, strategic planning and crucial decision making are heavily involved. Figure 8.10 below shows the finalised outline of the Company' development in the first year of establishment.

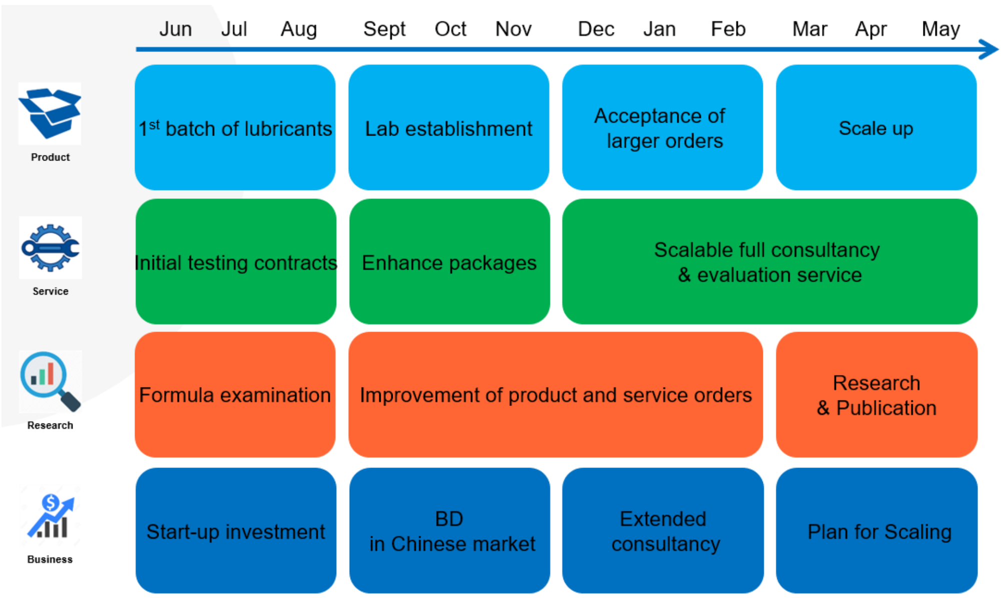

Figure 8.10. Outline for the Company business development in the 1st year

Within a period of 12 months, the Company aims to expand its capability in the key branches of product, service, research and business areas, while the four strategic development areas would be able to support each other for a sustainable growth of the business.

8.4.2. Risk management for the Company

A technology start-up company is naturally associated with risks from different perspectives. Table 8.6 is composed as a representative risk register in order to address and manage the identified risks for the Company.

Number	Risk category	Key description	Risk Level	Mitigation
1	Technical	Difficulties in formula testing and analysis	Medium	Upgrade testing facilities and improve technical know-how
2	Technical	Difficulties in procurement of base oils and additives	Low	Utilise both domestic and international procurement channels
3	Technical	Difficulties in on-time delivery of products/testing results	Medium	Manage delivery expectations in contracts
4	Technical	Challenges in obtaining overestimated product results	Low	Manage customer expectations and gather information about competitors' products
5	Technical	Difficulties in the funding of lab facilities	Medium	Ensure that investments in

				place for different phases
6	Technical	Lack of technician capability	Low	Ensure recruitment and training of technicians
7	Management	Key members leave the Company without notice	Low	Regular team-building and protection of the team integrity
8	Management	Excessive cost on operation	Medium	Realistic planning for the operational cost and secure investments
9	Management	Imbalanced development between Company strategies	Medium	Regular review of development; adjust when necessary
10	Management	Unforeseen difficulties affecting operations	Medium	Be flexible and reasonable; consult advisers accordingly
11	Research	Challenges of gap between research and delivery	Medium	Balanced input on research and commercial activities
12	Legal	Potential IP disputes	Medium	Ensure that necessary IP documented and protected

13	Social	Misunderstanding from the public on the environmental impact	Low	Ensure that the public is aware of the Company's activities for environmental protection
14	Security	Loss of facilities, data and other property	Low	Ensure that the security measures are adequate and up to date
15	Policy	Withdraw of policy supports	Low	Ensure that all promised supports are documented

Table 8.6. Risk Management for the Company

8.5. Added value and pathways to impact of the study

8.5.1. Added value of the study

The Company's research and commercial practices aim to create added value from academic and business perspectives. The application of the analogy-empowered creative design process for enterprise has been tested in the real-world case study of the establishment of a start-up company. The application evaluation suggests that a new connection is established between academic and business realms through analogical thinking, and the applicability and analogical thinking is also evaluated thanks to the assistance from SSM methodology. Evidently, further evaluation by other case studies will be necessary to apply success evaluation for the use of analogical thinking in business world, and this study acts as a good starting point for the new application.

Added value is also identifiable in the innovative transformation from scientific study to commercial realisation, particularly the technology-led innovation which should contribute to positive competition in the field of lubrication development. The customers will benefit from such competition for longer-term interests, rather than the attraction purely from lowered retailing prices. In short, it is believed that this study has added value to not only the research realm by realising the value of analogical thinking in enterprise design, but also the innovative translation from scientific research to real-world business application.

8.5.2. Pathways to impact

The Company, as a technology start-up, would try its best to survive and develop into a sustainable enterprise. Meanwhile, it has been made clear that sustainable development needs to involve the positive impact as a result, including technological, commercial and societal impact.

a. Pathway to technological impact

As described in the analogical thinking process for development and advancement of the Company's lubrication technology, it is not the specific formula but the reasons behind the formula that the Company would like to address and improve. This strategy enables fundamental applicability and diversity of the Company's lubricate solutions. Scientific research would be an essential pillar for the longer-term growth of the Company, and the input of resources into research would benefit continuously the technological development of lubrication research. The Company plans to publish generic scientific discoveries along with the progression of research, which could help to enhance the technological stance and contribute to the industry.

b. Pathway to commercial impact

The business model developed by the Company focuses on the delivery of both products and services. The initial lubricant products the Company provides cover the majority of existing application fields with extra focus on passenger cars. The commercial potentials are huge as there were approximately 217 million passenger cars in use in China by the end of 2017 (CIConsulting, 2018). In addition to the delivery of lubricants, the Company also offers consultancy on the evaluation of the technical working environment, and advice on the possible enhanced solutions. All proposed activities aim to help the Company to create a firm position in the market. Furthermore, the idea of sustainable development with consideration of environmental protection and energy saving could, as a result, have a commercial impact on the industry. A healthy and technology-led competition should benefit all customers and practitioners of the lubrication industry.

c. Pathway to societal impact

The Company's identification of market needs and gaps, with the help of analogical thinking, indicates the importance of understanding the actual working environment before applying the lubrication solutions. This ideology is different from the current common activities of the consumers as they tend to purchase and apply standard lubricants for generic applications, especially in the Chinese market. This behaviour will be less accurate in targeting the technical requirements, the waste of non-functional additives and little consideration of the environment. The Company proposes to precisely customise lubricants based on its actual working requirements and add consideration of the elements of environmental friendliness. The expected societal impact is of great potential, because customers will receive bespoke lubricant solutions without needing to pay extra for unfunctional additives within the formula and the environment will be able to benefit from the use of less harmful additives.

An overall illustration of the pathways to impacts is illustrated in Figure 8.11 below.

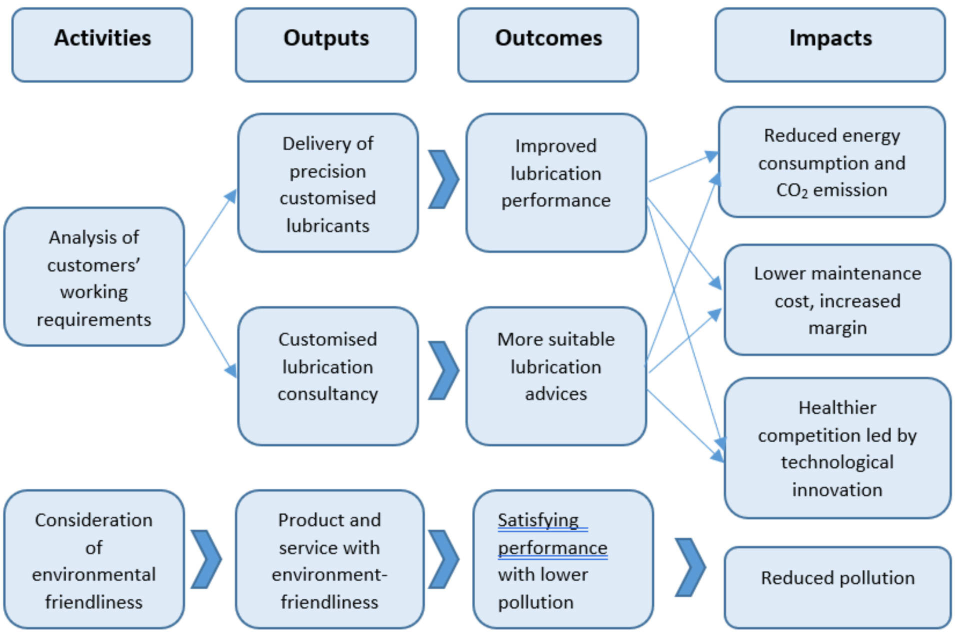

Figure 8.11. Pathways to impacts for the Company

8.6. Real-life initial evaluation of the start-up Company

The Company holds positive attitude towards the real-life evaluation and justification, as they reveal the outcome of a start-up business, and provide a direct and objective testing of the Company. The evaluation also indicates whether analogical thinking has been proven to be valuable in this case study of designing an enterprise.

In May 2019, the Company was invited to "Wuxi Summit of Talents and Innovation" which takes place in the city of Wuxi, China. This was a high-profile conference in the city of Wuxi to celebrate technological breakthroughs, entrepreneurship and innovation. The Company was honoured to be selected and invited to participate in this event as a promising start-up.

The Company pitched its technologies and business plan for the audience at the Summit and took advantage of this great opportunity to communicate with dozens of other enterprises, including start-up companies, SMEs and large corporations, for their insights in technology commercialisation and business development. The insights and tips gathered through the interviews are invaluable, and equally invaluable are the enterprises' ever positive attitude towards business development, their dedication to the improvement of products and services, and the ability of adaptation to changes. The Company has been fortunate to be able to evaluate the utilisation of analogical thinking in a real-life setting, while being offered the opportunity to gain invaluable insights and tips from fellow enterprises as an early stage start-up.

Evidence from both the researcher's own experience and feedback have suggested that analogy and analogical thinking could enhance the creativity for enterprise design. Approximately 90% of all the businesses interviewed by the researcher commented on the challenge of starting and developing a business. While every start-up would highly focus their resources on the complex and possibly frustrating process, especially at the early stage, the research on the application of analogical thinking in the establishment of businesses could potentially moderate the complexity of the enterprise growth journeys, especially for start-ups.

8.7. Conclusion and Discussion

The case study reported in this chapter forms the DS-II phase under the DRM research framework. It attempts to conduct an initial application evaluation for the proposed analogy-empowered creative design process for enterprise. Through the planning and actions towards the establishment of the start-up Company, the applicability and initial success of the analogical design process have been tested by the feedback within the business realm and the agreement from the market. Due to the environmental constraints of the case study (mainly limited time and business resources), the longer-term evaluation of the case study within the real business world is yet to be obtained. However, DRM suggests that an initial evaluation with applicable actions is satisfactory as DS-II phase conclusions following the consistency of the research methodology (Blessing and Chakrabarti, 2009) .

To summarise, analogical thinking has been adopted in the conceptual design phase of the Company, including the identification of market gap, the advancement of technology and the business model development (Table 8.7). These three challenges are identified by the analysis of SSM as key elements for the Company's development. The human-centred element of the proposed analogical design process is represented through the idea generation and decision making; for instance, the Company made strategic decisions to develop environmental-friendly formula for the lubrication solutions and consultant advices for services.

Key aspect	Source domain	Analogy	Target domain	Mapping
Market gap	Business	Bespoke suit	Fashion	Customisation
Technology adaption	Technology	Smart Little Persons (SLP)	Fantasy	Function enhancement
Business model development	Business	Tree	Nature	Morphological and functional mapping

Table 8.7. Analogies for key aspects of enterprise design for the Company

The application of analogical thinking in enterprise design has enhanced the strategic thinking process, not only in finding feasible solutions to challenges but also in providing the thinkers with a trackable and adaptable tool where continuous inspirations could be achieved. Thanks to analogical thinking, the researcher managed to find a possible set of solutions to business questions on market needs, technology and business model development in an efficient manner (see Section 8.4).

It is worth noting that the design of an enterprise, in particular a start-up company, is a complex task which requires a huge amount of creative ideation, decision making and, in addition to these challenges, risk taking. Such complex tasks could benefit from effective tools such as analogical thinking. This study does not intend to neglect the value of conventional business development methodologies but primarily to test the usefulness of analogy in the design of enterprise, especially in what is arguably the most challenging task of a start-up business establishment.

In addition to the intended evaluation of the analogy-empowered creative design process through a real-world case study for research rigour, the outcome of this study also contributes to the identification of a new realm of application of such design process, i.e. the design of enterprise. New insights as reported above have been obtained by the novel application of analogical thinking to real-world enterprise design, through the vehicle of analogy-empowered creative design process. These insights indicate both theoretical and practical value for application of analogical thinking in solving real challenges in the business world.

Chapter 9. Conclusions and Future Research

This Chapter summarises the key research findings reported in this thesis, identifies the resulting contributions to the knowledge including a new form of presentation of analogical thinking in creativity (ACP), a new angle for connection between creativity, design and analogy (analogy-empowered creative design process), as well as a new way of application of analogical thinking in enterprise design. Various impacts that these findings could lead to are also discussed. DRM, as the utilised research methodology, plays a crucial part in the regulation of the research boundary and implementation of research activities. Limitations of this research are strategically evaluated, while several directions for future work have been identified.

9.1. Research Conclusion

9.1.1. Key research findings

This study attempts to enhance human creativity in the context of design by promoting analogical thinking. Throughout the study, the Analogical Creative Process (ACP) is developed as a new form of presentation for analogy; analogical thinking is applied into real-world engineering design and enterprise design projects as a new type of application, thanks to the analogy-empowered creative design process which reflects the new angel for the connection identified between creativity, design and analogy; positive relations are discovered between analogical thinking and the creative output of enterprise design process, where a new way of connection is established between research and business domains.

This study is organised to find answers to the three research questions clarified in Chapter 5:

1. How effective is analogical thinking in the conceptual design ideation of a real-world engineering design project?
2. What is a possible form of integration of analogical thinking into the creative design; and for the purpose of application of analogical thinking in enterprise design, what evidence could demonstrate the existence of analogy in the enterprise context?

3. How to apply analogical thinking so that it can benefit a real-world enterprise design project?

The key findings of this study include:

a. Presentation of the interrelated connection between creativity, analogy and design.

Strategic reviews of creativity and analogy are conducted to gather fundamental understandings, which lead to the identification and elaboration of analogy in creativity and the insights of the establishment of analogy. Strategic reviews of cognitive creativity process and design process indicate that an organic integration output of creative design process is possible. Such integration potential was identified in Sections 2.1.2 and 7.2.3 for creative process and design process respectively. As the existence of analogy is in fields of design, an analogy-empowered creative design process would be logically feasible. It is the interrelations between creativity, analogy and design that provided the theoretical soil for the proposal of an analogy-empowered creative design process. These interrelations have been identified throughout the flow of the thesis and were illustrated in Figure 6.1, which also discloses the reasoning from such interrelations to the proposal of an analogy-empowered creative design process. These findings are the fundamental cornerstones on which the answers to the research questions are built.

The analogy-empowered creative design process is established through two phases:

1. To integrate cognitive creativity process with design process, in order to highlight the benefit of creativity in design while acknowledging the similarities of both processes. A typical creative process would consist of preparation, incubation, verification and evaluation as key stages (see Table 2.6), while a typical design process would involve exploration, conceptual design, embodiment and evaluation (see Table 7.3). The similarities of both processes exist not only at the structural level, but also in the cognitive process of delivering the creative output. Furthermore, the integration

potential is also supported by the continuous research focus on creativity in the design research realm.

2. To highlight analogical thinking, and then have it embedded into the creative design process. This is theoretically reasonable because, as presented in the previous chapters, analogy is within the creativity realm and can be identified in creativity tools and applications, and design-by-analogy has been heavily adopted. The common process of analogical thinking involves retrieval, mapping and transfer, which could potentially lead to the creative output of problem solving (see Table 3.5). Therefore, the analogy-empowered creative design process has been proposed in theory with a possible representative form illustrated in Figure 7.9. The evaluation of applicability and value of the process will require exploration through real-world design practice.

An application evaluation of the analogy-empowered creative design process is conducted by the design practice of enterprise. Through the new application of analogical thinking in the development of a technology start-up company, the applicability and usefulness of the proposed analogical thinking process are observed in the Action Research which is reported in Section 8.4. Soft Systems Methodology has been adopted to help deal with the complex design task of an enterprise with analogical thinking embedded into the conceptual design phase. Analogies have been established to enhance the idea generation for the identification of market requirements, the advancement of technology and the development of business model. The findings from this new type of application is encouraging and would be able to attract more research and application attentions to the field of analogical thinking in a business context. These findings relate to the second and third research questions identified.

b. The step-by-step expression of Analogical Creative Process (ACP) guideline.

The step-by-step structure of ACP enables it to systematically identify attributes and relations within the source domain and target domain, and to highlight the analogical mapping process as the key to analogical thinking. ACP is proposed based on Gentner's Structure Mapping Theory of analogy and prioritises relations to attributes when establishing analogical mapping between domains (see Section 3.2). ACP is expected to assist users to reach analogical output through the thinking process. The investigation of the establishment of analogy leads to the proposed expression form of ACP. The advantage is that users are not required to receive trainings about analogy or to obtain in-depth understandings of how analogy is established, because the structure of ACP helps break the analogical mapping into segments of tasks (see Chapter 5). Its step-by-step form would be able to guide the users through the establishment of analogy and achieve analogical output. The feedback from application of ACP in the engineering design project indicates that the flexibility and adaptability of ACP would make it suitable for users with different amount of experience in using analogy (see Section 6.4). Experienced users are suggested to refer to ACP as a guideline while inexperienced users could benefit from the step-by-step guidance. ACP, as a form of the application of analogical thinking, leads to the exploration of the answers to the research questions.

The outcome of the application of ACP in a real-world engineering design project shows the practical usefulness of ACP in addition to its theoretical value. ACP demonstrates its applicability and usefulness in idea generation of the conceptual design phase (see Section 6.4). Creative idea generation by analogical thinking has been observed with novelty and variety, which can enhance the outcome of idea generation by non-analogical creativity tools. The review of analogy indicates that analogical thinking in theory can benefit human creativity and design output, while the findings from this project echo the theoretical expectation of analogy in enhancing creative output in an engineering design task. These findings relate to the first research question.

c. Valuable experiences of strategic utilisation of Design Research Methodology (DRM) framework of design research.

DRM requires balanced research attention on outcome from literature review of existing work and findings from empirical studies. In order to ensure that the research has rigour, a sequence of studies including Descriptive Studies and Prescriptive Studies are essential and conducted within this study. The experience obtained from utilisation of other research methods such as Triangulation, MMR and SSM help to expand the arsenal of research tools for future work.

The collection of findings from this study addresses the research questions, leads to the contributions and impact of this study, and helps to indicate the directions of future work in analogical thinking.

9.1.2. Research contributions and impacts

Building on the foundation of the Initial Impact Model described in Section 3.9, the findings and contributions are expected to offer new insights through the answers to the identified research questions. An updated Impact Model can, as a result, be generated as illustrated in Figure 9.1. The development of ACP and the analogy-empowered creative design process have been applied in case studies of engineering and enterprise design, however, further research activities such as the enhancement of ACP as a theoretical method, as well as production of further derived theoretical support can also benefit the improvement to creative design.

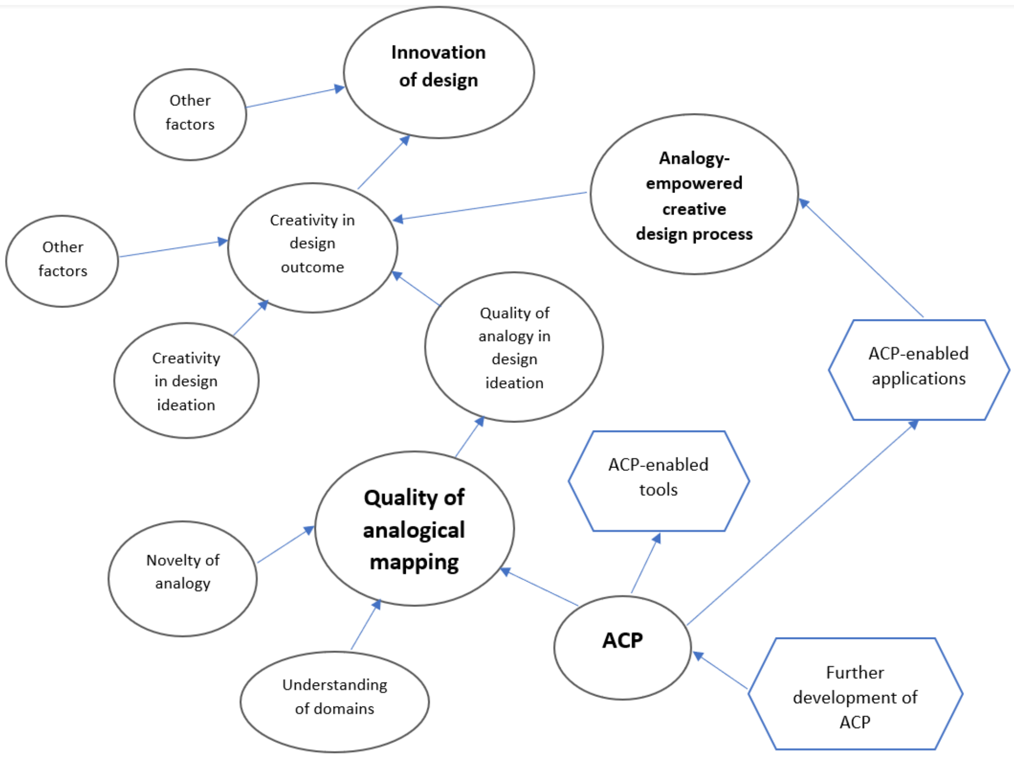

Figure 9.1. An updated Impact Model for the study

To present the findings and contributions in detail, this study aims to contribute to the knowledge of analogy in design from the following perspectives:

a. A new form of presentation of analogical thinking in creativity (ACP).

This new form is achieved by the development of the step-by-step ACP process to apply analogical thinking, and the findings from the application of ACP in tasks of engineering design and the design of enterprise. ACP is not meant to be a strict process for thinkers to follow, but is flexible and can either be referred to when necessary or followed as a guideline to conduct analogical thinking. ACP helps thinkers without an in-depth understanding of or experience with analogy, to be able to think analogically, thanks to its step-by-step structure of identifying and establishing analogical mapping (see Chapter 5). In addition to the existing direct use of analogy in design and computational use of analogy, ACP offers an alternative approach, which is established from the angle of structuring mapping of analogy, to benefit design research and practice.

b. The research outcome of the new way of application of analogical thinking in real-world tasks of engineering design and design of enterprise.

The application of analogical thinking in the engineering design project indicates the effectiveness of analogy compared with selected non-analogical creativity tools. The analogical tools lead to ideation outcome with higher novelty and variety (see Section 6.4.2). The outcome could inspire more research attention into the ACP form of the application of analogical thinking in design practice. As a complex design task, the development of the technology start-up company requires large amount of resources, management and method support, as identified in Section 8.3. The application evaluation of the analogy-empowered creative design process indicates the value of analogical thinking in a business context, and thanks to the use of analogical thinking, key challenges for the Company at early stage have been tackled, including areas of market clarification, technology development and the establishment of business model (see Section 8.4). These findings help to promote analogical thinking in business and could inspire further studies into this realm of application.

The analogy-empowered creative design process contributes to the knowledge as a new angle of connection between creativity, design and analogy on theoretical level. Analogy has been associated with creativity and utilised to enhance design, and as illustrated in Chapter 7, the analogy-empowered creative design process has the potential to improve the outcome of creative design activities. Such a new connection has been further evaluated in practice through application in enterprise design.

c. An application evaluation of DRM in design research.

DRM, as a comprehensive design methodology, is applied in the whole process of this study and helps to ensure the research rigour and completeness. However, this study is an example of application of DRM in design research, thus further justifies the theoretical soundness of DRM and its applicability. A contribution of this study could be identified as the promotion of DRM for its future adoption in design research.

The findings and contributions of this study could lead to the following set of impacts:

a. Impact to research

This study could lead to an impact on the development of research on creativity, analogy and design. The developed ACP does not require pre-training or in-depth understanding of the establishment of analogy, and so can be utilised by users as either a reference or a step-by-step guideline. The outcome of ACP will reflect the result of analogical thinking. Indicated by the effective use of analogical thinking in the engineering design project, the applicability and flexibility of ACP should help to attract more research attention and promote the application of analogical thinking in creativity and design. The application evaluation of the analogy-empowered creative design process has demonstrated initial success in its applicability and effectiveness in the design of enterprise. This could encourage more findings of application of analogical thinking in design. This study hopes that research featuring analogical thinking and aiming to solve real-world design problems should get more attention from the research community.

b. Impact to business world

The potential impact to the business world is identifiable from the case study of founding a functioning start-up company with the assistance of analogical thinking. In this case study, challenges in three areas are identified and tackled using analogical thinking, including the clarification of market needs, the advancement of technology and the decision-making on business model (see Section 8.4). Given that these are common business challenges facing companies, the assistance from analogical thinking is suggested for circumstances such as reported in this study. This is enabled by a new connection between research and business domains linked by the analogy-empowered creative design process. This study has suggested that the value of analogical thinking not only exists in research but also in a commercial setting. It would be reasonable to envisage that analogical thinking can help to solve business problems, not limited to the identification of market requirements, the development of technology and the business model, and this ability will be enhanced with the supports of data and evidence from further research and application. The impact from this study to the business world relies on the awareness of analogical thinking by the practitioners. The increased added value would be expected once analogical thinking is utilised more in the business world.

c. Impact to society and environment

The public can benefit from increased use of analogical thinking in general creative problem solving, as analogical thinking has already existed in realms of creativity and design (see Chapter 2, 3 and 7). The increased awareness of analogical thinking by the public is related to enhanced creativity in general problem solving. The case study described in Chapter 7 used analogical thinking to choose directions of technology advancement and business model; the human-centred element of the analogy-empowered creative design process suggests that elimination of surplus additives is desirable for saving resources and protecting the environment. The optimised formula of lubrication solutions will increase the productivity while reducing the cost of maintenance; the reduced use of environmentally harmful additives of the lubricants leads to the positive impact to environment protection.

The impact on both society and the environment would have a huge potential should the lubricant product and service of the Company continue to grow and scale up. Furthermore, larger positive impact is expected when the business competitors will need to catch up by producing optimised lubrication solutions with minimum harm to the environment in the long term.

9.1.3. Limitations

Throughout this study, three main limitations were experienced.

a. Limited opportunities were available to conduct design research with the intended participants including both individuals and organisations. Suitable research cases are limited and suitable participants for the research cases were also limited.

   For instance, to collect data on the effectiveness of analogical thinking, a real-world engineering design project is adopted to fulfil the research purposes. The constraints, such as research time and resources, on this case study limited the size of design team and the participants' capability of input for this study. Although satisfactory findings are achieved through careful planning and implementation of research enhanced by the method of triangulation, improvement can be expected should a team with more suitable members be deployed and the participants' capability of input increases.

   A similar limitation is experienced while conducting studies on the application of analogical thinking in the context of enterprise. It has been challenging to involve enterprises in the research activities as participants. Two main reasons are identified for this situation: 1) Companies are concerned about their input for the proposed study, including labour, time and information, especially when little direct benefit such as an increase of profit can be guaranteed by the researcher. 2) Companies are concerned about data confidentiality even though they are assured that the data collected are solely for research purposes and will not be disclosed to any third party. This is understandable since start-up companies are cautious about the data of their technologies, market research and business models. Commercial sensitivity has led to extra challenges experienced by the researcher due to the concerns from the potential participant companies for this study. A cohort of 16 SMEs eventually agreed to participate and provide valid data, although a larger cohort would have been more desirable.

b. The application of ACP is with limited output due to the scope and resources of this study. ACP should have a larger research and application potential due to the ease of use, and, as a guided step-by-step process ACP requires little pre-training prior to using analogical thinking. The applications of ACP reported in this study are for engineering design and for design of enterprise. No other domains of design are explored for the application of ACP; the domains of engineering design and design of enterprise would also be able to benefit from further research and application of ACP.
c. The study of the application of analogical thinking in a real-world enterprise design has been conducted, although it suffers from the limitation of time. Therefore, no continuous monitoring and improvement is possible for the growth of the established start-up company for research purposes. For this case study, Application Evaluation is implemented to test the applicability and initial usefulness of analogical thinking in design of enterprise. Due to the time limitation of the research, Success Evaluation is not possible to be achieved, which requires a long-term ongoing evaluation of the development of the start-up company.

In addition to the limitations identified above, there are limitations on the rigor of research caused by, for instance, participant bias and coding bias, as discussed in relation to research quality in Section 4.3, and mitigated accordingly in the case studies.

9.2. Directions for future research

9.2.1. Further development of ACP and ACP-enabled tools

The introduction of ACP and the analogy-empowered creative design process have led to initial achievements in engineering design and the design of enterprise. However, only limited experiences are available so far for the application of these processes, thus further development and improvement are necessary. It would be essential to apply the processes as tools to more diversified real-world design scenarios to gather insights into its applicability and effectiveness. In addition, it would also be helpful to promote the tools to the design research community so that other researchers' thoughts for improvement are made available.

ACP as a method has been proved of value in enhancing creativity output in design through application of analogical thinking. Given that ACP is better explored and understood in this study, it would be sensible to suggest further research attention and activity on ACP so that new creativity tools can be potentially enabled. In line with the research trends on analogical thinking in design, it is possible to computerise ACP and develop software which reflect the systematicity and use of analogical thinking. Computational approach has been a research topic to enhance design by analogy (see Section 3.5). A computational approach to guide the designer through ACP could be an attempt with potential, as the interaction between users and computers, compared to following a guidance of diagram, can improve the user experience of ACP. In addition, the method of ACP can potentially be embedded in creativity and design education so that analogical thinking is made more available and accessible.

Another direction for potential improvement is through theoretical research of the processes. For instance, should a well-established domain of analogy be available to the designers and design researchers as the suggested source domain of ACP, its application would be more likely to take place. For the theoretical improvement of the analogy-empowered creative design process, further studies could be focused on the analyses of the most influential elements for design tasks, and the embedding of such elements into design practices. It is envisaged that, for different types of design tasks, should the prioritised design requirements be different, a certain degree of flexibility would thus be beneficial when choosing the integrated elements of the process for specific design practices. The theoretical improvements of the processes would need to be based on further studies on investigation and evaluation, and the potential improvement would reduce the limitations identified in the processes.

9.2.2. Further application of analogical thinking in real-world design projects

This study has reported the application of analogical thinking in an engineering design project and a project of enterprise design with satisfactory findings. In order to increase the validity of findings, further iteration of evaluation through real-world design projects are preferable, as is suggested in DRM research methodology. The iterations include applications of analogical thinking in the two design domains with existing evidence and in other unexplored domains of design. Further evaluations do not necessarily need to be implemented through lengthy projects and well-established design tasks. In fact, the effectiveness of analogical thinking can be expected to benefit all kinds of design practices, from simple to complex ones, because analogical thinking enhances designer's creativity, and creativity leads to improved design with elements of novelty, usefulness, and surprise.

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Appendix 1. TRIZ Contradiction Matrix in Chinese

TRIZ 矛盾矩阵 TRIZ Contradiction Matrix

每个会变差的参数→		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
↓每个会变好的参数			所有	15 8 29 34	所有	29 17 38 34	所有	29 2 40 28	所有	2 8 15 38	8 10 18 37	10 36 37 40	10 14 35 40	1 35 19 39	28 27 18 40	5 34 31 35	所有	6 29 4 38	19 1 32	35 12 34 31	所有	12 36 18 31	6 2 34 19	5 35 3 31	10 24 35	10 35 20 28	3 26 18 31	1 3 11 27	28 27 35 26	28 35 26 18	22 21 18 27	22 35 31 39	27 28 1 36	35 3 2 24	2 27 28 11	29 5 15 8	26 30 36 34	28 29 26 32	26 35 18 19	35 3 24 37
		所有		所有	10 1 29 35	所有	35 30 13 2	所有	5 35 14 2	所有	8 10 19 35	13 29 10 18	13 10 29 14	26 39 1 40	28 2 10 27	所有	2 27 19 6	28 19 32 22	19 32 35	所有	18 19 28 1	15 19 18 22	18 19 28 15	5 8 13 30	10 15 35	10 20 35 26	19 6 18 26	10 28 8 3	18 26 28	10 1 35 17	2 19 22 37	35 22 1 39	28 1 9	6 13 1 32	2 27 28 11	19 15 29	1 10 26 39	25 28 17 15	2 26 35	1 28 15 35
3	运动部分的长度	8 15 29 34	所有		所有	15 17 4	所有	7 17 4 35	所有	13 4 8	17 10 4	1 8 35	1 8 10 29	1 8 15 34	8 35 29 34	19	所有	10 15 19	32	8 35 24	所有	1 35	7 2 35 39	4 29 23 10	1 24	15 2 29	29 35	10 14 29 40	28 32 4	10 28 29 37	1 15 17 24	17 15	1 29 17	15 29 35 4	1 28 10	14 15 1 16	1 19 26 24	35 1 26 24	17 24 26 16	14 4 28 29
4	静止部分的长度	所有	35 28 40 29	所有		所有	17 7 10 40	所有	35 8 2 14	所有	28 10	1 14 35	13 14 15 7	39 37 35	15 14 28 26	所有	1 10 35	3 35 38 18	3 25	所有	所有	12 8	6 28	10 28 24 35	24 26	30 29 14	所有	15 29 28	32 28 3	2 32 10	1 18	所有	15 17 27	2 25	3	1 35	1 26	26	所有	30 14 7 26
5	运动部分的面积	2 17 29 4	所有	14 15 18 4	所有		所有	7 14 17 4	所有	29 30 4 34	19 30 35 2	10 15 36 28	5 34 29 4	11 2 13 39	3 15 40 14	6 3	所有	2 15 16	15 32 19 13	19 32	所有	19 10 32 18	15 17 30 26	10 35 2 39	30 26	26 4	29 30 6 13	29 9	26 28 32 3	2 32	22 33 28 1	17 2 18 39	13 1 26 24	15 17 13 16	15 13 10 1	15 30	14 1 13	2 36 26 18	14 30 28 23	10 26 34 2
6	静止部分的面积	所有	30 2 14 18	所有	26 7 9 39	所有		所有	所有	所有	1 18 35 36	10 15 36 37	所有	2 38	40	所有	2 10 19 30	35 39 38	所有	所有	所有	17 32	17 7 30	10 14 18 39	30 16	10 35 4 18	2 18 40 4	32 35 40 4	26 28 32 3	2 29 18 36	27 2 39 35	22 1 40	40 16	16 4	16	15 16	1 18 36	2 35 30 18	23	10 15 17 7
7	运动部分的体积	2 26 29 40	所有	1 7 4 35	所有	1 7 4 17	所有		所有	29 4 38 34	15 35 36 37	6 35 36 37	1 15 29 4	28 10 1 39	9 14 15 7	6 35 4	所有	34 39 10 18	2 13 10	35	所有-	35 6 13 18	7 15 13 16	36 39 34 10	2 22	2 6 34 10	29 30 7	14 1 40 11	25 26 28	25 28 2 16	22 21 27 35	17 2 40 1	29 1 40	15 13 30 12	10	15 29	26 1	29 26 4	35 34 16 24	10 6 2 34
8	静止部分的体积	所有	35 10 19 14	19 14	35 8 2 14	所有	所有	所有		所有	2 18 37	24 35	7 2 35	34 28 35 40	9 14 17 15	所有	35 34 38	35 6 4	所有	所有	所有	30 6	所有	10 39 35 34	所有	35 16 32 18	35 3	2 35 16	所有	35 10 25	34 39 19 27	30 18 35 4	35	所有	1	所有	1 31	2 17 26		35 37 10 2
9	速度	2 28 13 38	所有	13 14 8	所有	29 30 34	所有	7 29 34	所有		13 28 15 19	6 18 38 40	35 15 18 34	28 33 1 18	8 3 26 14	3 19 35 5	所有	28 30 36 2	10 13 19	8 15 35 38	所有	19 35 38 2	14 20 19 35	10 13 28 38	13 26	所有	10 19 29 38	11 35 27 28	28 32 1 24	10 28 32 25	1 28 35 23	2 24 35 21	35 13 8 1	32 28 13 12	34 2 28 27	15 10 26	10 28 4 34	3 34 27 16	10 18	所有
10	力	8 1 37 18	18 13 1 28	17 19 9 36	28 10	19 10 15	1 18 36 37	15 9 12 37	2 36 18 37	13 28 15 12		18 21 11	10 35 40 34	35 10 21	35 10 14 27	19 2	所有	35 10 21	所有	19 17 10	1 16 36 37	19 35 18 37	14 15	8 35 40 5	所有	10 37 36	14 29 18 36	3 35 13 21	35 10 23 24	28 29 37 36	1 35 40 18	13 3 36 24	15 37 18 1	1 28 3 25	15 1 11	15 17 18 20	26 35 10 18	36 37 10 19	2 35	3 28 35 37
11	压力或压强	10 36 37 40	13 29 10 18	35 10 36	35 1 14 16	10 15 36 28	10 15 36 37	6 35 10	35 24	6 35 36	36 35 21		35 4 15 10	35 33 2 40	9 18 3 40	19 3 27	所有	35 39 19 2	所有	14 24 10 37	所有	10 35 14	2 36 25	10 36 3 37	所有	37 36 4	10 14 36	10 13 19 35	6 28 25	3 35	22 2 37	2 33 27 18	1 35 16	11	2	35	19 1 35	2 36 37	35 24	10 14 35 37
12	形状	8 10 29 40	15 10 26 3	29 34 5 4	13 14 10 7	5 34 4 10	所有	14 4 15 22	7 2 35	35 15 34 18	35 10 37 40	34 15 10 14		33 1 18 4	30 14 10 40	14 26 9 25	所有	22 14 19 32	13 15 32	2 6 34 14	所有	4 6 2	14	35 29 3 5	所有	14 10 34 17	36 22	10 40 16	28 32 1	32 30 40	22 1 2 35	35 1	1 32 17 28	32 15 26	2 13 1	1 15 29	16 29 1 28	15 13 39	15 1 32	17 26 34 10
13	结构稳定性	21 35 2 39	26 39 1 40	13 15 1 28	37	2 11 13	39	28 10 19 39	34 28 35 40	33 15 28 18	10 35 21 16	2 35 40	22 1 18 4		17 9 15	13 27 10 35	39 3 35 23	35 1 32	32 3 27 16	13 19	27 4 29 18	32 35 27 31	14 2 39 6	2 14 30 40	所有	35 27	15 32 35	所有	13	18	35 24 30 18	35 40 27 39	35 19	32 35 30	2 35 10 16	35 30 34 2	2 35 22 26	35 22 39 23	1 8 35	23 35 40 3
14	强度	1 8 40 15	40 26 27 1	1 15 8 35	15 14 28 26	3 34 40 29	9 40 28	10 15 14 7	9 14 17 15	8 13 26 14	10 18 3 14	10 3 18 40	10 30 35 40	13 17 35		27 3 26	所有	30 10 40	35 19	19 35 10	35	10 26 35 28	35	35 28 31 40	所有	29 3 28 10	29 10 27	11 3	3 27 16	3 27	18 35 37 1	15 35 22 2	11 3 10 32	32 40 25 2	27 11 3	15 3 32	2 13 25 28	27 3 15 40	15	29 35 10 14
15	运动部分的作用时间	19 5 34 31	所有	2 19 9	所有	3 17 19	所有	10 2 19 30	所有	3 35 5	19 2 16	19 3 27	14 26 28 25	13 3 35	27 3 10		所有	19 35 39	2 19 4 35	28 6 35 18	所有	19 10 35 38	所有	28 27 3 18	10	20 10 28 18	3 35 10 40	11 2 13	3	3 27 16 40	22 15 33 28	21 39 16 22	27 1 4	12 27	29 10 27	1 35 13	10 4 29 15	19 29 39 35	6 10	35 17 14 19
16	静止部分的作用时间	所有	6 27 19 16	所有	1 40 35	所有	所有	所有	35 34 38	所有	所有	所有	所有	39 3 35 23	所有	所有		19 18 36 40	所有	所有	所有	16	所有	27 16 18 38	10	28 20 10 16	3 35 31	34 27 6 40	10 26 24	所有	17 1 40 33	22	35 10	1	1	2	所有	25 34 6 35	1	20 10 16 38
17	温度	36 22 6 38	22 35 32	15 19 9	15 19 9	3 35 39 18	35 38	34 39 40 18	35 6 4	2 28 36 30	35 10 3 21	35 39 19 2	14 22 19 32	1 35 32	10 30 22 40	19 13 39	19 18 36 40		32 30 21 16	19 15 3 17	所有	2 14 17 25	21 17 35 38	21 36 29 31	所有	35 28 21 18	3 17 30 39	19 35 3 10	32 19 24	24	22 33 35 2	22 35 2 24	26 27	26 27	4 10 16	2 18 27	2 17 16	3 27 35 31	26 2 19 16	15 28 35
18	光照强度	19 1 32	2 35 32	19 32 16	所有	19 32 26	所有	2 13 10	所有	10 13 19	26 19 6	所有	32 30	32 3 27	35 19	2 19 6	所有	32 35 19		32 1 19	32 35 1 15	32	13 16 1 6	13 1	1 6	19 1 26 17	1 19	所有	11 15 32	3 32	15 19	35 19 32 39	19 35 28 26	28 26 19	15 17 13 16	15 1 19	6 32 13	32 15	2 26 10	2 25 16
19	运动部分能耗	12 18 28 31	所有	12 28	所有	15 19 25	所有	35 13 18	所有	8 15 35	16 26 21 2	23 14 25	12 2 29	19 13 17 24	5 19 9 35	28 35 6 18	所有	19 24 3 14	2 15 19		所有	6 19 37 18	12 22 15 24	35 24 18 5	所有	35 38 19 18	34 23 16 18	19 21 11 27	3 1 32	所有	1 35 6 27	2 35 6	28 26 30	19 35	1 15 17 28	15 17 13 16	2 29 27 28	35 38	32 2	12 28 35
20	静止部分能耗	所有	19 9 6 27	所有	所有	所有	所有	所有	所有	所有	36 37	所有	所有	27 4 29 18	35	所有	所有	所有	19 2 35 32	所有		所有	所有	28 27 18 31	所有	所有	3 35 31	10 36 23	所有	所有	10 2 22 37	19 22 18	1 4	所有	所有	所有	所有	19 35 16 25	所有	1 6
21	功率	8 36 38 31	19 26 17 27	1 10 35 37		19 38	17 32 13 38	35 6 38	30 6 25	15 35 2	26 2 36 35	22 10 35	29 14 2 40	35 32 15 31	26 10 28	19 35 10 38	16	2 14 17 25	16 6 19	16 6 19 37	所有		10 35 38	28 27 18 38	10 19	35 20 10 6	4 34 19	19 24 26 31	32 15 2	32 2	19 22 31 2	2 35 18	26 10 34	26 35 10	35 2 10 34	19 17 34	20 19 30 34	19 35 16	28 2 17	28 35 34
22	能量耗散	15 6 19 28	19 6 18 9	7 2 6 13	6 38 7	15 26 17 30	17 7 30 18	7 18 23	7	16 35 38	36 38	所有	所有	14 2 39 6	26	所有	所有	19 38 7	1 13 32 15	所有	所有	3 38		35 27 2 37	19 10	10 18 32 7	7 18 25	11 10 35	32	所有	21 22 35 2	21 35 2 22	所有	35 32 1	2 19	所有	7 23	35 3 15 23	2	28 10 29 35
23	物质的损耗	35 6 23 40	35 6 22 32	14 29 10 39	10 28 24	35 2 10 31	10 18 39 31	1 29 30 36	3 39 18 31	10 13 28 38	14 15 18 40	3 36 37 10	29 35 3 5	2 14 30 40	35 28 31 40	28 27 3 18	27 16 18 38	21 36 39 31	1 6 13	35 18 24 5	28 27 12 31	28 27 18 38	35 27 2 31		所有	15 18 35 10	6 3 10 24	10 29 39 35	16 34 31 28	35 10 24 31	33 22 30 40	10 1 34 29	15 34 33	32 28 2 24	2 35 34 27	15 10 2	35 10 28 24	35 18 10 13	35 10 18	28 35 10 23
24	信息的流失	10 24 35	10 35 5	1 26	26	30 26	30 16		2 22	26 32		所有	所有	所有	所有	10	10	所有	19	所有	所有	10 19	19 10	所有		24 26 28 32	24 28 35	10 28 23	所有	所有	22 10 1	10 21 22	32	27 22	所有	所有	所有	35 33	35	13 23 15
25	时间的耗费	10 20 37 35	10 20 26 5	15 2 29	30 24 14 5	26 4 5 16	10 35 17 4	2 5 34 10	35 16 32 18	所有	10 37 36 5	37 36 4	4 10 34 17	35 3 22 5	29 3 28 18	20 10 28 18	28 20 10 16	35 29 21 18	1 19 26 17	35 38 19 18	1	35 20 10 6	10 5 18 32	35 18 10 39	24 26 28 32		35 38 18 16	10 30 4	24 34 28 32	24 26 28 18	35 18 34	35 22 18 39	35 28 34 4	4 28 10 34	32 1 10	35 28	6 29	18 28 32 10	24 28 35 30	所有
26	材质/事物的数量	35 6 18 31	27 26 18 35	29 14 35 18	所有	15 14 29	2 18 40 4	15 20 29	所有	35 29 34 28	35 14 3	10 36 14 3	35 14	15 2 17 40	14 35 34 10	3 35 10 40	3 35 31	3 17 39	所有	34 29 16 18	3 35 31	35	7 18 25	6 3 10 24	24 28 35	35 38 18 16		18 3 28 40	13 2 28	33 30	35 33 29 31	3 35 40 39	29 1 35 27	35 29 25 10	2 32 10 25	15 3 29	3 13 27 10	3 27 29 18	8 35	13 29 3 27
27	可靠性	3 8 10 40	3 10 8 28	15 9 14 4	15 29 28 11	17 10 14 16	32 35 40 4	3 10 14 24	2 35 24	21 35 11 28	8 28 10 3	10 24 35 19	35 1 16 11	所有	11 28	2 35 3 25	34 27 6 40	3 35 10	11 32 13	21 11 27 19	36 23	21 11 26 31	10 11 35	10 35 29 39	10 28	10 30 4	21 28 40 3		32 3 11 23	11 32 1	27 35 2 40	35 2 40 26	所有	27 17 40	1 11	13 35 8 24	13 35 1	27 40 28	11 13 27	1 35 29 38
28	测量精度	32 35 26 28	28 35 25 26	28 26 5 16	32 28 3 16	26 28 32 3	26 28 32 3	32 13 6	所有	28 13 32 24	32 2	6 28 32	6 28 32	32 35 13	28 6 32	28 6 32	10 26 24	6 19 28 24	6 1 32	3 6 32	所有	3 6 32	26 32 27	10 16 31 28	所有	24 34 28 32	2 6 32	5 11 1 23		所有	28 24 22 26	3 33 39 10	6 35 25 18	1 13 17 34	1 32 13 11	13 35 2	27 35 10 34	26 24 32 28	28 2 10 34	10 34 28 32
29	加工精度	28 32 13 18	28 35 27 9	10 28 29 37	2 32 10	28 33 29 32	2 29 18 36	32 23 2	25 10 35	10 28 32	28 19 34 36	3 35	32 30 40	30 18	3 27	3 27 40	所有	19 26	3 32	32 2	所有	32 2	13 32 2	35 31 10 24	所有	32 26 28 18	32 30	11 32 1	所有		26 28 10 36	4 17 34 26	所有	1 32 35 23	25 10	所有	26 2 18	所有	26 28 18 23	10 18 32 39
30	外部有害因素	22 21 27 39	2 22 13 24	17 1 39 4	1 18	22 1 33 28	27 2 39 35	22 23 37 35	34 39 19 27	21 22 35 28	13 35 39 18	22 2 37	22 1 3 35	35 24 30 18	18 35 37 1	22 15 33 28	17 1 40 33	22 33 35 2	1 19 32 13	1 24 6 27	10 2 22 37	19 22 31 2	21 22 35 2	33 22 19 40	22 10 2	35 18 34	35 33 29 31	27 24 2 40	28 33 23 26	26 28 10 18		所有	24 35 2	2 25 28 39	35 10 2	35 11 22 31	22 19 29 40	22 19 29 40	33 3 34	22 35 13 24
31	产生的有害因素	19 22 15 39	35 22 1 39	17 15 16 22	所有	17 2 18 39	22 1 40	17 2 40	30 18 35 4	35 28 3 23	35 28 1 40	2 33 27 18	35 1	35 40 27 39	15 35 22 2	15 22 33 31	21 39 16 22	22 35 2 24	19 24 39 32	2 35 6	19 22 18	2 35 18	21 35 2 22	10 1 34	10 21 29	1 22	3 24 39 1	24 2 40 39	3 33 26	4 17 34 26	所有		所有	所有	所有	所有	19 1 31	2 21 27 1	2	22 35 18 39
32	制造难易度	28 29 15 16	1 27 36 13	1 29 13 17	15 17 27	13 1 26 12	16 40	13 29 1 40	35	35 13 8 1	35 12	35 19 1 37	1 28 13 27	11 13 1	1 3 10 32	27 1 4	35 16	27 26 18	28 24 27 1	28 26 27 1	1 4	27 1 12 24	19 35	15 34 33	32 24 18 16	35 28 34 4	35 23 1 24		1 35 12 18	所有	24 2	所有		2 5 13 16	35 1 11 9	2 13 15	27 26 1	6 28 11 1	8 28 1	35 1 10 28
33	操作难易度	25 2 13 15	6 13 1 25	1 17 13 12	所有	1 17 13 16	18 16 15 39	1 16 35 15	4 18 39 31	18 13 34	28 13 35	2 32 12	15 34 29 28	32 35 30	32 40 3 28	29 3 8 25	1 16 25	26 27 13	13 17 1 24	1 13 24	所有	35 34 2 10	2 19 13	28 32 2 24	4 10 27 22	4 28 10 34	12 35	17 27 8 40	25 13 2 34	1 32 35 23	2 25 28 39	所有	2 5 12		12 26 1 32	15 34 1 16	32 26 12 17	所有	1 34 12 3	15 1 28
34	维修难易度	2 27 35 11	2 27 35 11	1 28 10 25	3 18 31	15 13 32	16 25	25 2 35 11	1	34 9	1 11 10	13	1 13 2 4	2 35	11 1 2 9	11 29 28 27	1	4 10	15 1 13	15 1 28 16	所有	15 10 32 2	15 1 32 19	2 35 34 27	所有	32 1 10 25	2 28 10 25	11 10 1 16	10 2 13	25 10	35 10 2 16	所有	1 35 11 10	1 12 26 15		7 1 4 16	35 1 13 11	所有	34 35 7 13	1 32 10
35	适应性或多功能性	1 6 15 8	19 15 29 16	35 1 29 2	1 35 16	35 30 29 7	15 16	15 35 29	所有	35 10 14	15 17 20	35 16	15 37 1 8	35 30 14	35 3 32 6	13 1 35	2 16	27 2 3 35	6 22 26 1	19 35 29 13	所有	19 1 29	18 15 1	15 10 2 13	所有	35 28	3 35 15	35 13 8 24	35 5 1 10	所有	35 11 32 31	所有	1 13 31	15 34 1 16	1 16 7 4		15 29 37 28	1	27 34 35	35 28 6 37
36	装置复杂程度	26 30 34 36	2 26 35 39	1 19 26 24	26	14 1 13 16	6 36	34 26 6	1 16	34 10 28	26 16	19 1 35	29 13 28 15	2 22 17 19	2 13 28	10 4 28 15	所有	2 17 13	24 17 13	27 2 29 28	所有	20 19 30 34	10 35 13 2	35 10 28 29	所有	6 29	13 3 27 10	13 35 1	2 26 10 34	26 24 32	22 19 29 40	19 1	27 26 1 13	27 9 26 24	1 13	29 15 28 37		15 10 37 28	15 1 24	12 17 28
37	监测的难易度	27 26 28 13	6 13 28 1	16 17 26 24	26	2 13 18 17	2 39 30 16	29 1 4 16	2 18 26 31	3 4 16 35	30 28 40 19	35 36 37 32	27 13 1 39	11 22 39 30	27 3 15 28	19 29 39 25	25 34 6 35	3 27 35 16	2 24 26	35 38	19 35 16	18 1 16 10	35 3 15 19	1 18 10 24	35 33 27 22	18 28 32 9	3 27 29 18	27 40 28 8	26 24 32 28	所有	22 19 29 28	2 21	5 28 11 29	2 5	12 26	1 15	15 10 37 28		34 21	35 18
38	自动化的程度	28 26 18 35	28 26 35 10	14 13 17 28	23	17 14 13	所有	35 13 16	所有	28 10	2 35	13 35	15 32 1 13	18 1	25 13	6 9	所有	26 2 19	8 32 19	2 32 13	所有	28 2 27	23 28	35 10 18 5	35 33	24 28 35 30	35 13	11 27 32	28 26 10 34	28 26 18 23	2 33	2	1 26 13	1 12 34 3	1 35 13	27 4 1 35	15 24 10	34 27 25		5 12 35 26
39	单位时间的生产率	35 26 24 37	28 27 15 3	18 4 28 38	30 7 14 26	10 26 34 31	10 35 17 7	2 6 34 10	35 37 10 2	所有	28 15 10 36	10 37 14	14 10 34 40	35 3 22 39	29 28 10 18	35 10 2 18	20 10 16 38	35 21 28 10	26 17 19 1	35 10 38 19	1	35 20 10	28 10 29 35	28 10 35 23	13 15 23	所有	35 38	1 35 10 38	1 10 34 28	18 10 32 1	22 35 13 24	35 22 18 39	35 28 2 24	1 28 7 10	1 32 10 25	1 35 28 37	12 17 28 24	35 18 27 2	5 12 35 26	

说明: 空白处表示所建议原则不存在; 尝试其它的矛盾项. “所有”表示不存在有意义的原则; 尝试其它的矛盾项。

40 条创新原则 1 分割原则 2 拆出原则 3 局部性质原则 4 不对称原则 5 联合原则 6 多功能原则 7 嵌套原则 8 配重原则 9 预先反作用原则 10 预先作用原则 11"预先放枕头"原则 12 等势原则 13"反向"原则 14 球形原则 15 动态原则 16 局部作用/过量作用原则 17 引入另一维度原则 18 机械振动原则 19 周期作用原则 20 连续有益作用原则 21 跃过原则 22 变害为利原则 23 反馈原则 24"中介者"原则 25 自我服务原则 26 复制原则 27 低成本短期代替原则 28 代替力学原理原则 29 气动与液压原则 30 软壳和薄膜原则 31 利用多孔材料原则 32 改变颜色原则 33 一致原则 34 部分剔除和再生原则 35 改变物体聚合态原则 36 相变原则 37 利用热膨胀原则 38 利用强氧化剂原则 39 采用惰性介质原则 40 利用混合材料原则

1 使用 39 个参数来确定问题中起决定性作用的一点。2 找出两个参数相互之间产生的矛盾点。3 使用矛盾矩阵来指出解决当前矛盾所能够采用的原则。4 依据矩阵中的数字在解决问题的原则中找到相应的项目，然后再据此找出解决问题的方法。

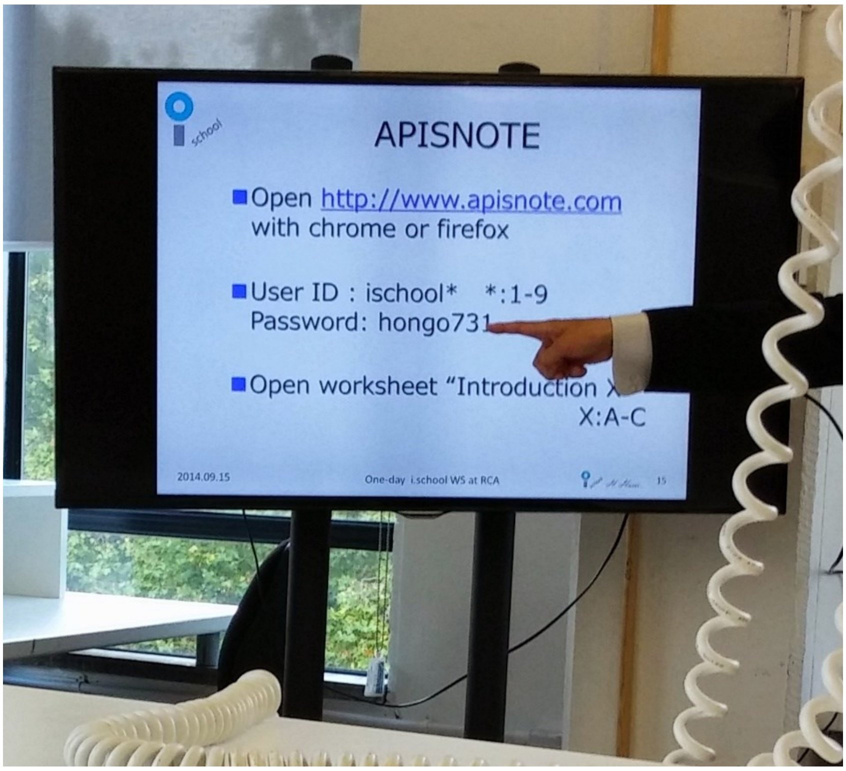
Peter Childs, Pengfei Mi 2017

Appendix 2. Experience design for behaviour change using APISNOTE and analogical thinking

The one-day workshop held in IDE studio at RCA consists of three key contents: 1. Introduction and application of the web-based tool APISNOTE; 2. Facilitated both general ideation and ideation with analogical thinking, and comparison; 3. To utilise APISNOTE in case study of behaviour change. All the contents are recorded and reviewed in detail as follows.

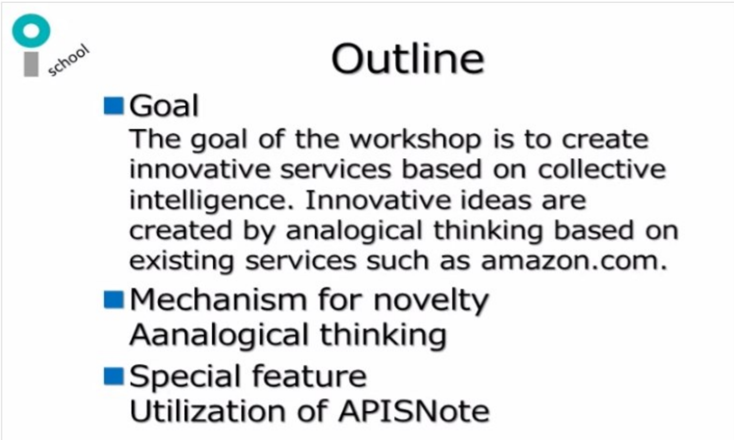
1. i.school of Tokyo University was founded in 2009, with the aim of teaching people to be more creative and innovative, and therefore realise and achieve new value. The summer school welcomes students from all over the world to be guided into being more creative.

   The APISNOTE is a web-based tool developed by i.school, which embeds practical functions and features contributing to an effective post-it ideation (picture 1). The main merits include remote group ideation, capture of ideation history, editing and categorization of ideas using colours, etc. Since APISNOTE is web-based, it works seamlessly among PCs and MACs. The remote function is yet to be tested.



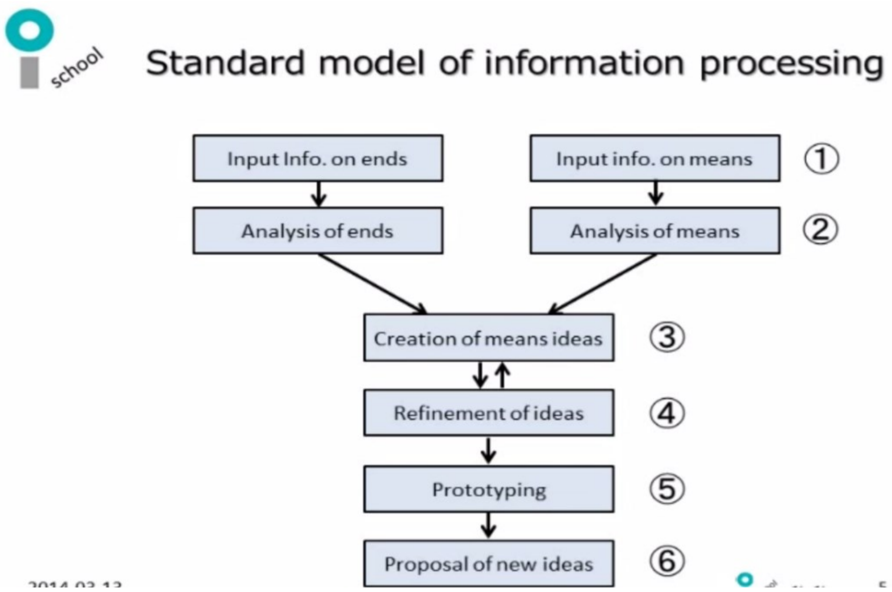
Picture 1. APISNOTE access address and log-in information

2. Participants are firstly presented with the outline of workshop (picture 2), then are guided through the APISNOTE basic functions, such as to choose from 7 colours as coloured Post-it notes, to publish the notes on the canvas, and to move and categorise them. One limitation here is that once a note is published, it cannot be edited. This is likely due to the potential heavy online data traffic should this feature exist.



Picture 2. Outline of i.school workshop

The workshop focuses mainly on the first 2 steps of Professor Horri's model of information processing, which are input of means and analysis of means (picture 3).



Picture 3. Horri's standard model of information processing

Professor Horri's mechanisms for novelty include Understanding others, Foresight, Clarifying concepts, Shifting cognitive pattern, Shifting value system, Finding new combination, Analogical thinking, New objective from unexpected use and Table flipping. Analogical thinking is promoted and tested at the workshop with the utilisation of APISNOTE.

To compare general ideation with ideation with analogical thinking, one same scenario of shopping mall is virtually adopted. At the stage of general ideation, a 5-minute video of shopping mall is played, and the participants are encouraged to generate as many ideas of potential services that could be provided in the shopping mall as possible using APISNOTE post-it as the scenes change within the shopping mall. This general ideation exercise is similar to brainwriting, only with the help of software. When the video finishes, all the ideas generated by each participant are recorded and grouped.

Prior to carrying out ideation with analogical thinking, examples of Amazon books and conveyor belt sushi bar are introduced to demonstrated analogy, where both have the mechanisms of tracking product acceptance and analyse data for future marketing (picture 4). Here an analogical mapping is clearly established between source domain (Amazon) and target domain (Conveyor belt sushi bar). No attributes are mapped over, but instead, the mechanisms of collecting data from previous marketing events and using the data for future marketing are the relations mapped over the domains.

Upon understanding the analogy from Amazon to Conveyor belt sushi bar, the participants are encouraged to watch the same video of shopping mall for 3 minutes for ideas of potential available services, only this time ideation should not be general but be analogical. The participants then publish ideas on APISNOTE and discuss with peers. According to the feedback from groups, the idea generation with analogical thinking feels easier compared to general divergent ideation, and the quality of analogical ideas are of higher degree of novelty and usefulness.

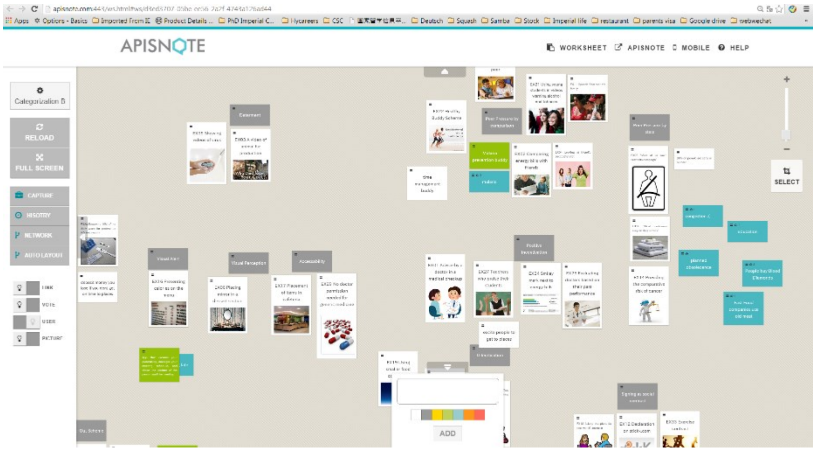
Taylormade proposal

Amazon	Conveyor belt sushi bar
Books	Sushi
Click buttons or browse pages	Insert dishes with QR code or IC tag on the back
Provided Value ・Propose books of my favorite	Provided Value ・My favorite sushi comes when I want it.
Mechanism of value provision ・Database of information browsing history and purchase history and analysis of similar customer data	Mechanism of value provision ・Database from QR code or IC tag attached to the back of the dishes and analysis of similar customer data
Incentive of data provision ・Just browse and buy	Incentive of data provision ・Just eat

Picture 4. Analogical mapping between Amazon and Conveyor belt sushi bar

3. The second half of the workshop concentrates on behaviour changes by ideas generated using analogical thinking. The participants are provided with 35 scenarios where people's behaviours are changed by strategies such as peer pressure, financial incentive, or baiting and guilt, etc. Each of the three groups is to choose one behaviour that should be changed, and then all group members generate novel ideas to achieve the change. This idea generation phase must utilise analogical thinking, and the most feasible idea with top novelty and impact are decided by voting.

   The key of this practice is how to establish effective mapping of analogy from existing mechanisms of example scenarios. A shortcut for establishing appropriate analogical mapping in the workshop is introduced, which is to first analyse and categorise the mechanisms and strategies of given behaviour-change scenarios. This preliminary work provides the thinkers, especially those with less experiences of analogical thinking, with clear analogical relations to map over (Picture 5). As an experienced thinker who realises analogy as a powerful tool, I suggested to consider 'stop being late' as the topic of behaviour change, with the cause that almost all the mechanisms of given categorisations could be mapped over from using analogical thinking. While other group members also suggested typical behaviour change topics, the final topic was chosen as 'stop being late' by vote.

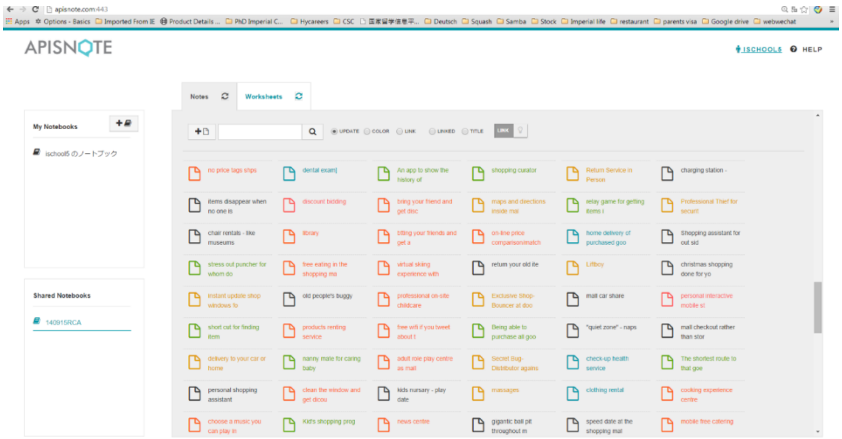


Picture 5. Behaviour change scenarios categorised in APISNOTE

The group presents the behaviour change scenario ‘stop being late’ by acting in a skit. A play is set up as working environment in a typical office, and one colleague is late with a smart phone application which is designed to change his behaviour of being late constantly. The application has features generated by mapping over given mechanisms as follows.

a. Visual alert and visual perception (EX06, EX16). The APP has an alert clock/countdown clock to remind user of not being late.
b. Peer pressure by comparison (EX02, 04, 11, 15, 21, 22)/Determent (EX03, 35). One interface of the APP shows live communication between other meeting colleagues, so that their images and voice messages can appear on the phone.
c. Peer pressure by statistics (EX05, 14, 20). One interface of the APP shows weekly statistics of being late for various occasions (work, relationship, casual, transport, etc.)
d. Signing as social contract (EX09, 10, 12, 18, 33)/Money as incentive (EX23, 24). One interface of the APP communicates with user’s friends or colleagues for live agreements of not being late; funds will be added to or deducted from the user’s account based on performance.
e. Positive Incentive (EX01, 25, 27, 34)/ guilt (EX32). One interface of the APP offers encouragement/praise for the user for not being late; and/or shows loss for being late.

All input and edit activities are captured and recorded in APISNOTE, so that the idea generation and collaboration can be identified with the axis of time, including both individual ideation and group discussion/voting(Picture 6).

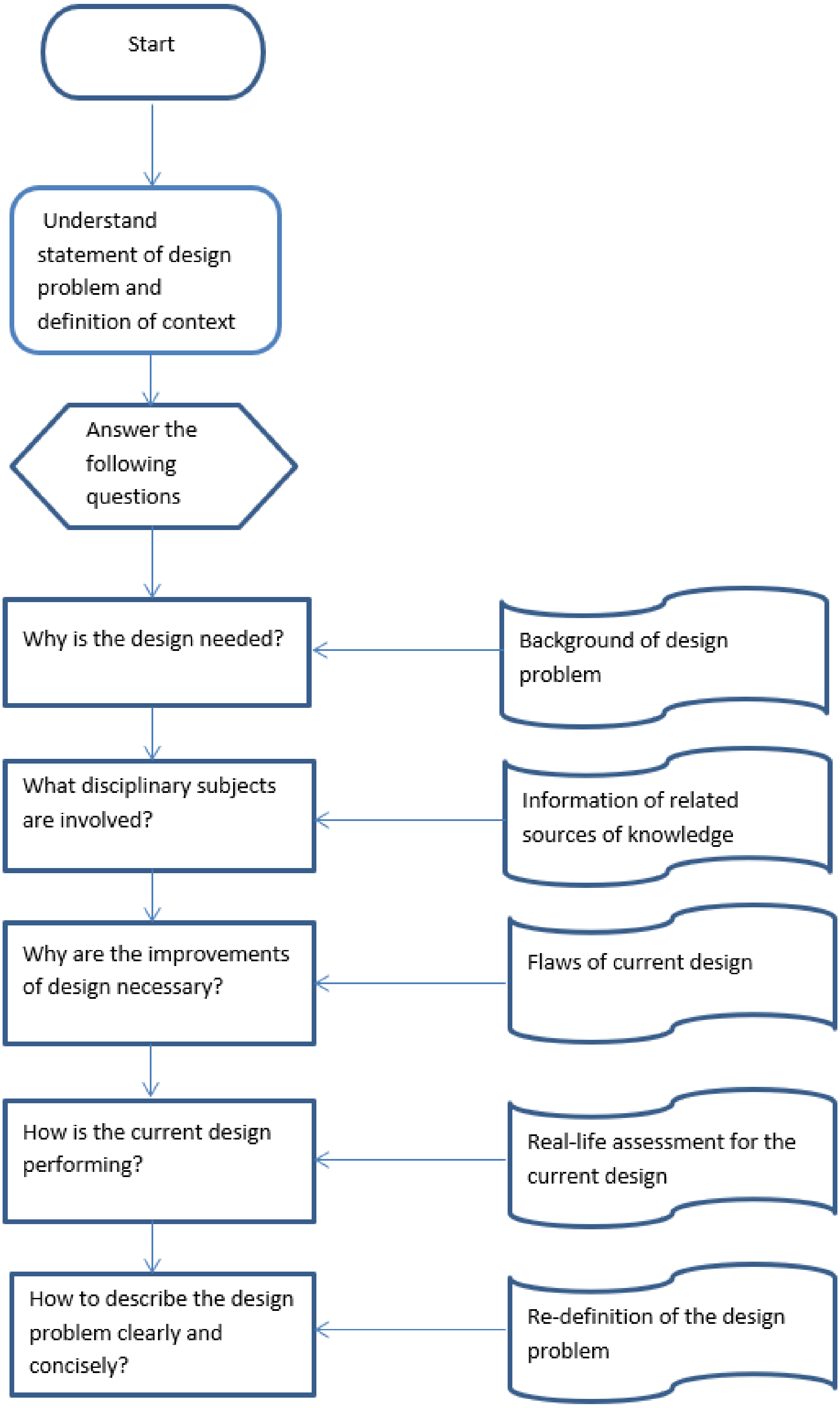


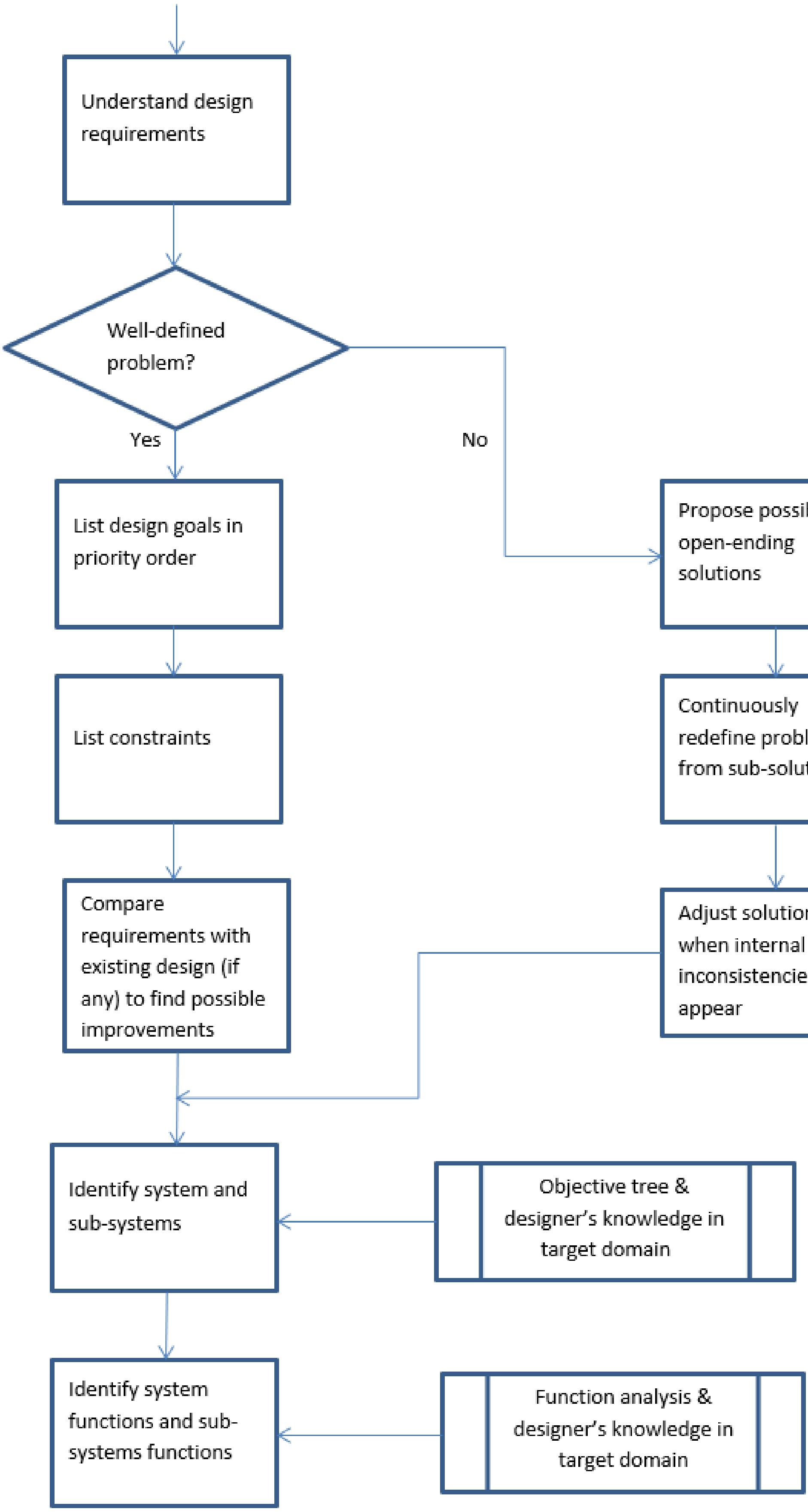
Picture 6. Historical notes of post-it captured in APISNOTE

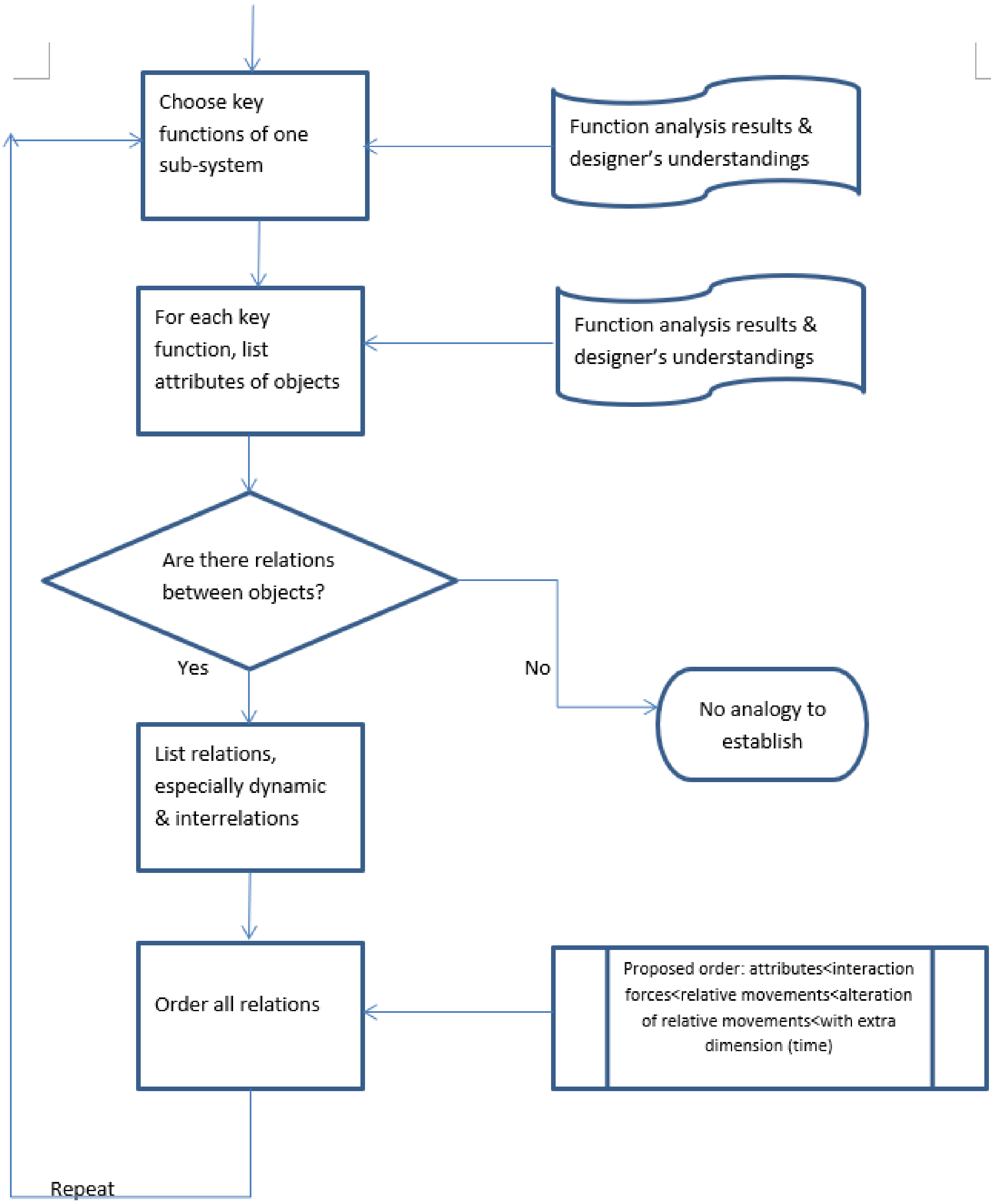
Summary

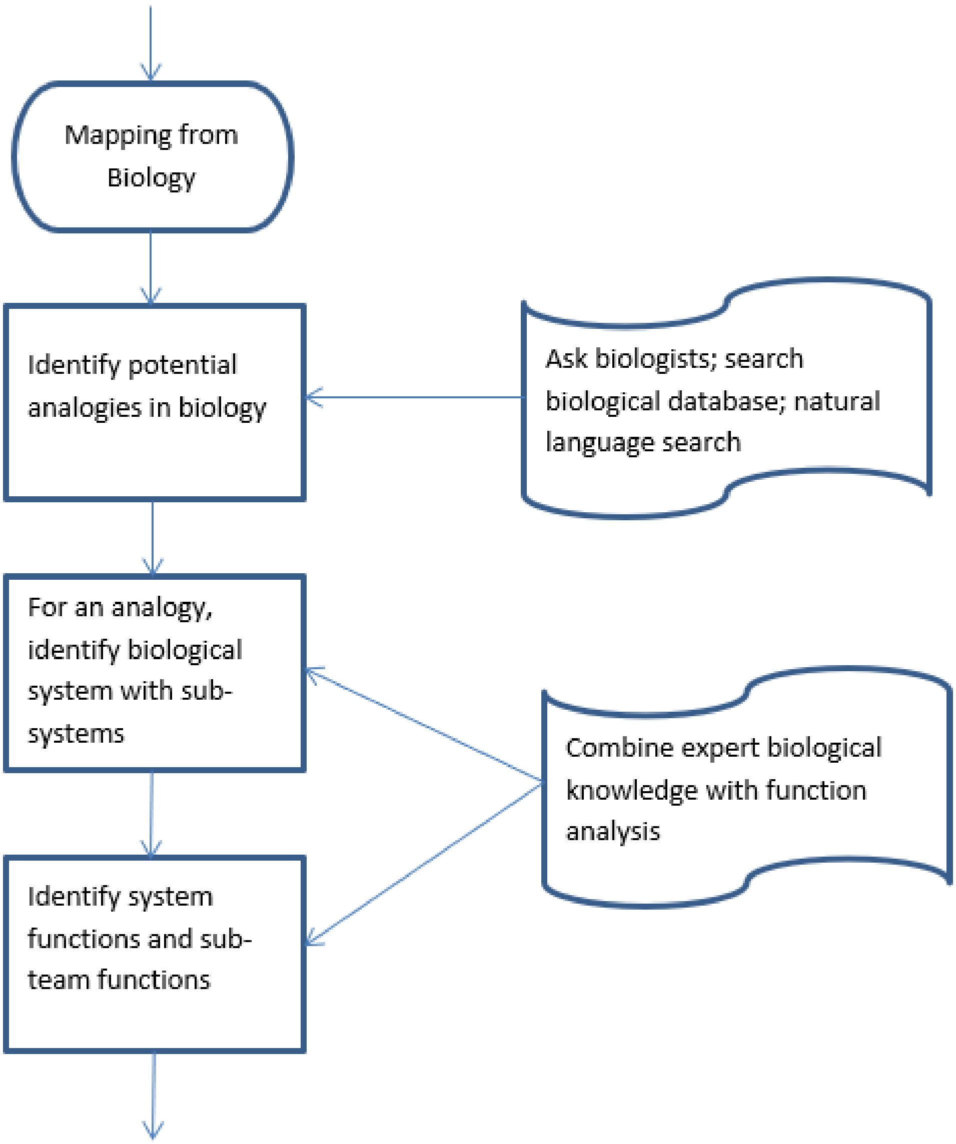
The i.school workshop is a fruitful creativity experience featuring ideation tool APISNOTE and analogical thinking. Two main outcomes that could benefit my own research would be 1. The workshop provides qualitative evidence that analogical thinking works well for guided ideation, even among participants with a little or no experience or training. However, although comparison of general ideation and ideation with analogical thinking are adopted in the workshop, no quantitative data is given on quality or quantity of ideas generated. And this data would be extremely evident in demonstrating the power of analogy in creativity. 2. The APISNOTE's feature of capturing historical activities could be useful for my next-step case study, where data of how analogical thinking take effect on both novice and experienced designers need to be collected and analysed. To combine video recording with APISNOTE, the data should be more thorough and accurate.

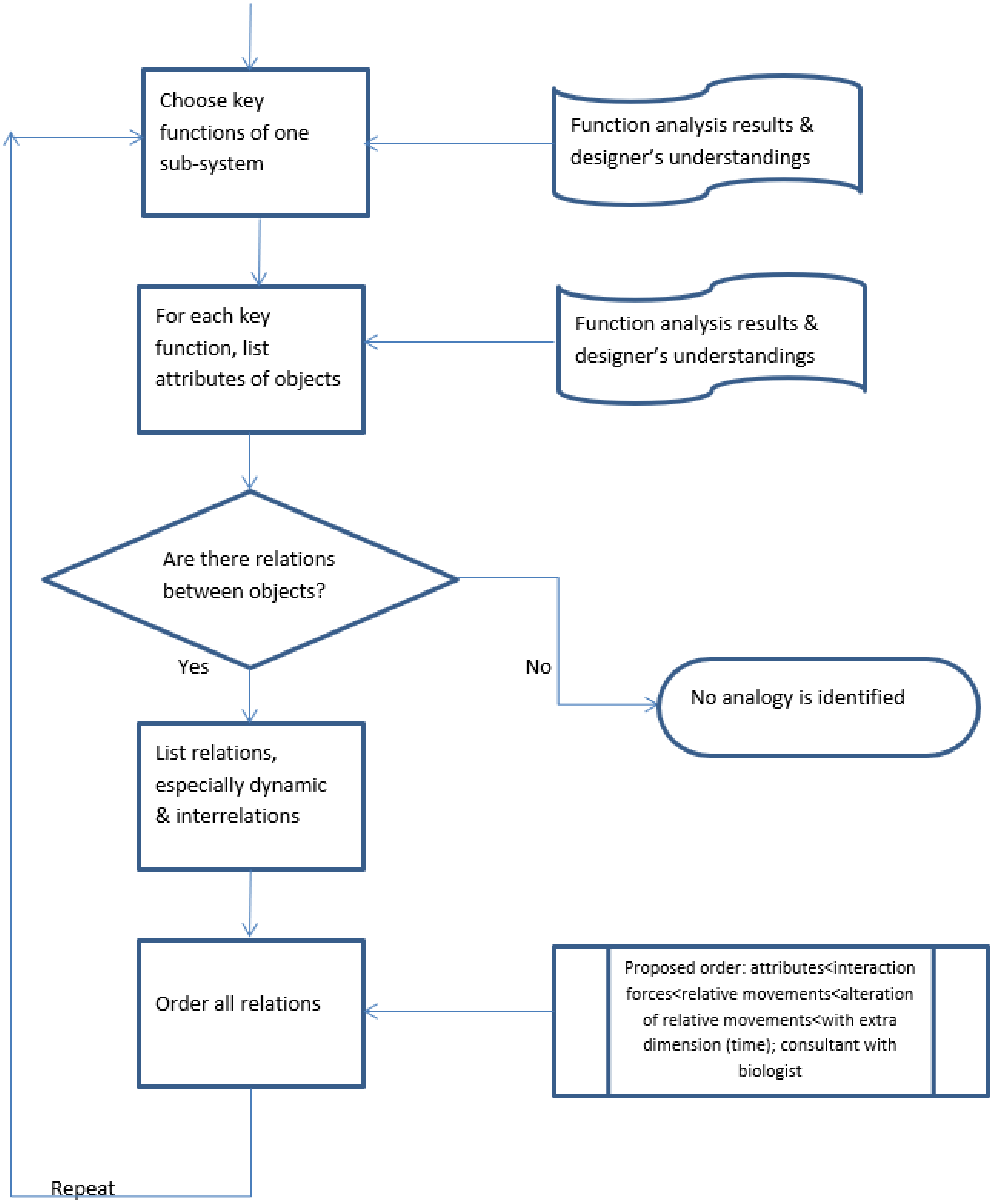
Appendix 3. A version of Analogical Creative Process (ACP) for design

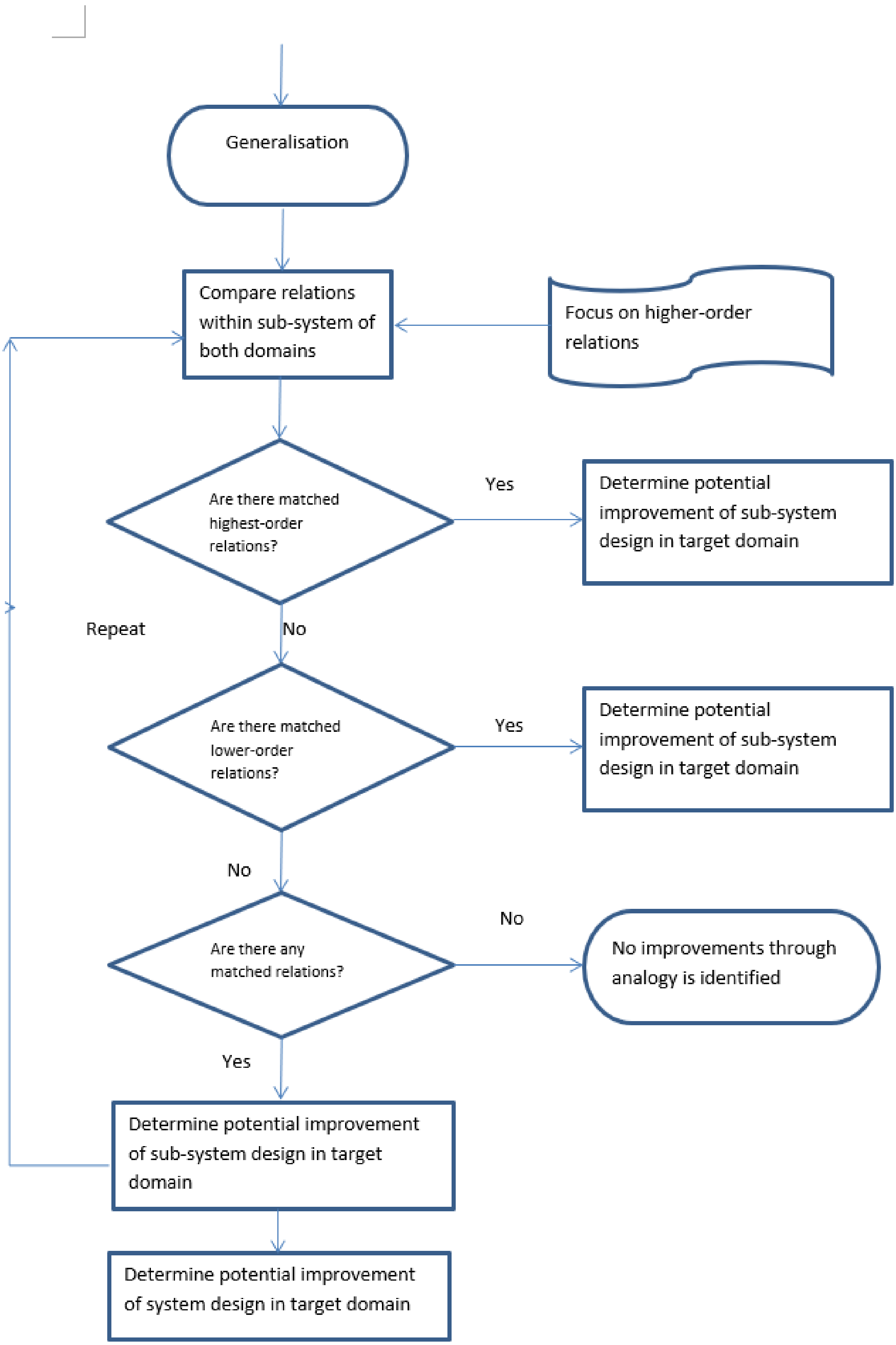


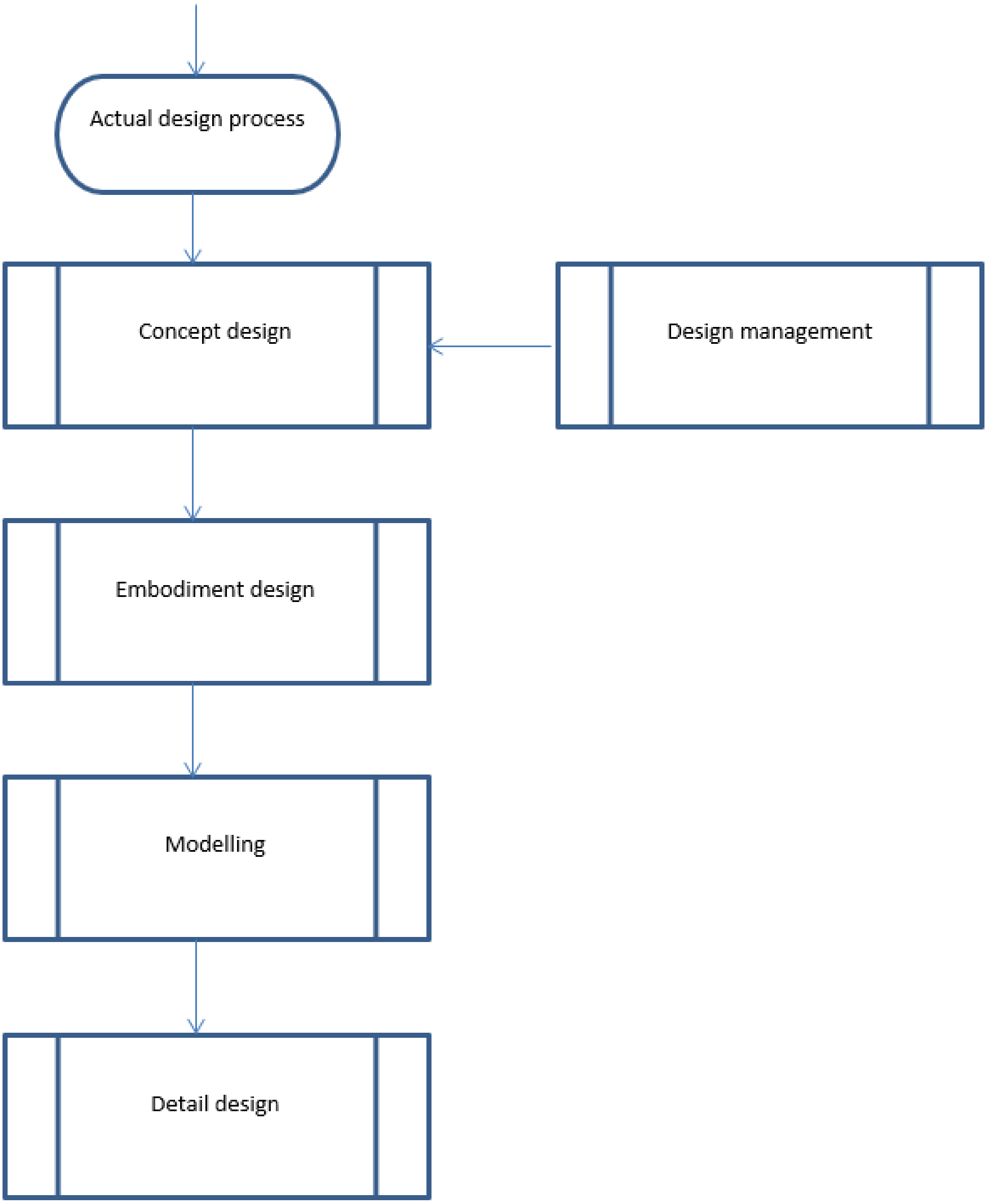

Understand design requirements
Well-defined problem?
Yes
No
List design goals in priority order
Propose possible open-ending solutions
List constraints
Continuously redefine problem from sub-solutions
Compare requirements with existing design (if any) to find possible improvements
Adjust solutions when internal inconsistencies appear
Identify system and sub-systems
Objective tree & designer's knowledge in target domain
Identify system functions and sub-systems functions
Function analysis & designer's knowledge in target domain

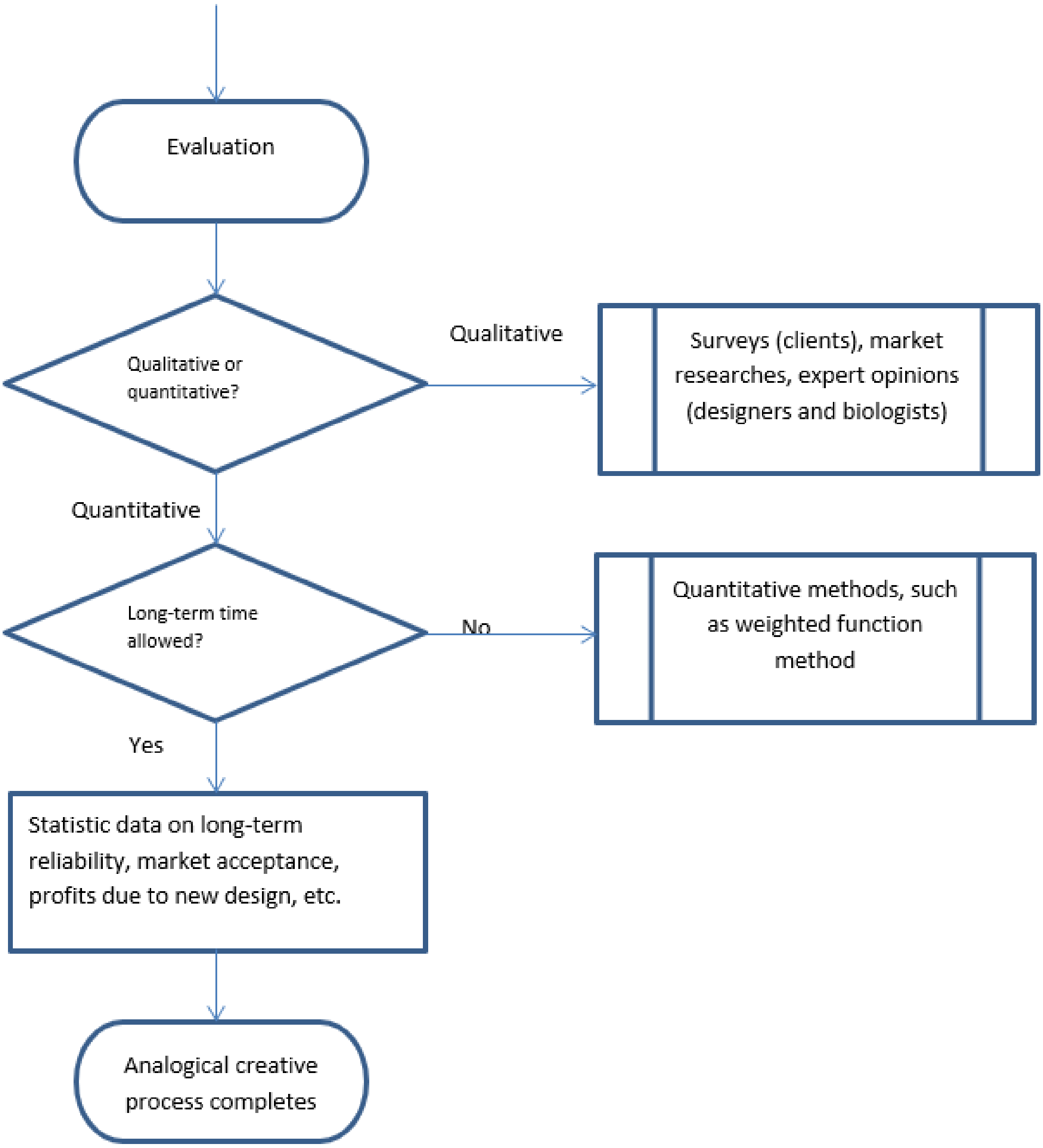

Choose key functions of one sub-system
Function analysis results & designer’s understandings
For each key function, list attributes of objects
Function analysis results & designer’s understandings
Are there relations between objects?
Yes
No
No analogy to establish
List relations, especially dynamic & interrelations
Order all relations
Proposed order: attributes<interaction forces<relative movements<alteration of relative movements<with extra dimension (time)
Repeat


Mapping from Biology
Identify potential analogies in biology
Ask biologists; search biological database; natural language search
For an analogy, identify biological system with sub-systems
Combine expert biological knowledge with function analysis
Identify system functions and sub-team functions


Choose key functions of one sub-system
Function analysis results & designer's understandings
For each key function, list attributes of objects
Function analysis results & designer's understandings
Are there relations between objects?
Yes
No
No analogy is identified
List relations, especially dynamic & interrelations
Order all relations
Proposed order: attributes<interaction forces<relative movements<alteration of relative movements<with extra dimension (time); consultant with biologist
Repeat


Generalisation
Compare relations within sub-system of both domains
Focus on higher-order relations
Are there matched highest-order relations?
Yes
Determine potential improvement of sub-system design in target domain
Repeat
No
Are there matched lower-order relations?
Yes
Determine potential improvement of sub-system design in target domain
No
Are there any matched relations?
No
No improvements through analogy is identified
Yes
Determine potential improvement of sub-system design in target domain
Determine potential improvement of system design in target domain


Actual design process
Concept design
Design management
Embodiment design
Modelling
Detail design


Evaluation
Qualitative or quantitative?
Qualitative
Surveys (clients), market researches, expert opinions (designers and biologists)
Quantitative
Long-term time allowed?
No
Quantitative methods, such as weighted function method
Yes
Statistic data on long-term reliability, market acceptance, profits due to new design, etc.
Analogical creative process completes

Appendix 4. Consent Form for Research for Engineering Design Project

Project: Application of analogical thinking in Design

Name of researcher: Pengfei Mi (desolenator project team);   Please initial box

1.	I agree to take part in the above Imperial College London research project. I have had the project explained to me, and I have read the participant information sheet, which I may keep for my records. I understand this will involve: • Be interviewed by the researcher • Allow the interview to be videotaped • Make myself available for a further interview should that be required	
2.	This information will be held and processed for the following purpose(s): to explore the effectiveness of analogy and analogical thinking when applied into design, and to derive further analysis based on these applications. I understand that any information I provide is confidential, and none of my personal information during this research will be published without my consent. No identifiable data will be shared with any other organisation without my consent.	
3.	I understand that my participation is on voluntary basis, and I could choose to participate in or withdraw from any part of the research study with advance notice.	
4.	I agree to Imperial College London recording the information about me and only use this information for purposes stated above, under the Data Protection Act 1998.	
5.	I agree to participate in the above study.	

Name of Participant

Signature

Date

Appendix 5. Consent to academic publication relating Desolenator

发件人:william janssen <william@desolenator.com>

发送时间: 12 November 2019 17:49

收件人:Mi, Pengfei

主题: Re: 答复: academic publish relating Desolenator

Lovely Pengfei,

Please proceed, this is fine,

Thanks,

w

On 12/11/2019 18:43, Mi, Pengfei wrote:

Hi William,

Thanks for your reply and please see attached document for your information.

Thanks.

Best wishes,

Pengfei

发件人: william janssen <william@desolenator.com>

发送时间: 12 November 2019 12:52

收件人: Mi, Pengfei <p.mi@imperial.ac.uk>

主题: Re: academic publish relating Desolenator

Dear Pengfei,

Thanks for your mail. in principle of course we have to objection to this request.

I would however ask that you share the text before publication.

It is a little difficult to visualise what it is gong to look like right now,

Many thanks,

william

On 12/11/2019 12:41, Mi, Pengfei wrote:

Dear William,

Hope you are very well.

In 2015 we as a team at Imperial College London provided some contractual technical support for the proof of concept for Desolenator. We enjoyed the experience and hopefully our work helped Desolenator on its technical soundness.

Now an academic thesis is emerging and part of it would like to include this project as a theoretical case study purely on the creative ideation for product design. Thus no technical solution or outcome regarding Desolenator is to be disclosed. Your consent is much appreciated. Please get back to me at your earliest convenience and feel free to let me know if you have any questions. Thanks.

Best wishes,

Pengfei Mi

Dyson School of Design Engineering

Imperial College London

07912 603176

p.mi@imperial.ac.uk

Appendix 6. Interviewing notes with selected SMEs on analogical thinking

The original notes from interviews with SMEs on analogical thinking are illustrated in this document. Among all 16 SMEs interviewed a cohort of 8 enterprises granted clear consent for publishing the records. The company names within the following records are symbolised by capital letters to observe the confidentiality and anonymity, in line with the research ethics principles this study applies as described in Section 4.3.1.

1. SME--A

SME-A is a project which aims to offer children multi-faceted education programmes which they would not typically access at school. They specialise in extra-curricular courses which run through 10 sessions, that help students craft and develop the skills associated with that specific programme.

Students are encouraged to explore their potentials in a supportive learning environment with exercises that could help enhance confidence and creativity. The latest technologies have been applied in the courses for both online and offline education sessions to provide the students with a full range of educational experiences.

I. Market gap. 7y. Soft skills.

Not get from school education, gap

step by step. 6 points → 6 courses,

deeper level clicked category 25y

help from experts & kids.

II. Tech. Lego (coding), (VR course).

universal language not applicable,

balance between peer learning & technology. teacher

x amounts. technology with heart

III. business. (Hard)

mistake. course before technology.

niche. expensive, licence to school

tided in jump in with everybody

motivation, (study right) Story of Kenya runner BBC.

family (team). carry you on.

2. SME-B

SME-B is about revolution of time. A new concept of smartwatch is developed to improve users' productivity and time management, so that they can spend time on the things that matter to them the most. The mission is to change people's perspective of time, ensure a more fulfilling life by using countdown for the most important tasks and goals of a day, a week or even a year.

I. time management. coach time

brainstorming, death watch, countdown

finite resource. compare other products

II Tech. hardware is hard. OEM.

tricks on price, churse

software, dedicated. insulate from other weather

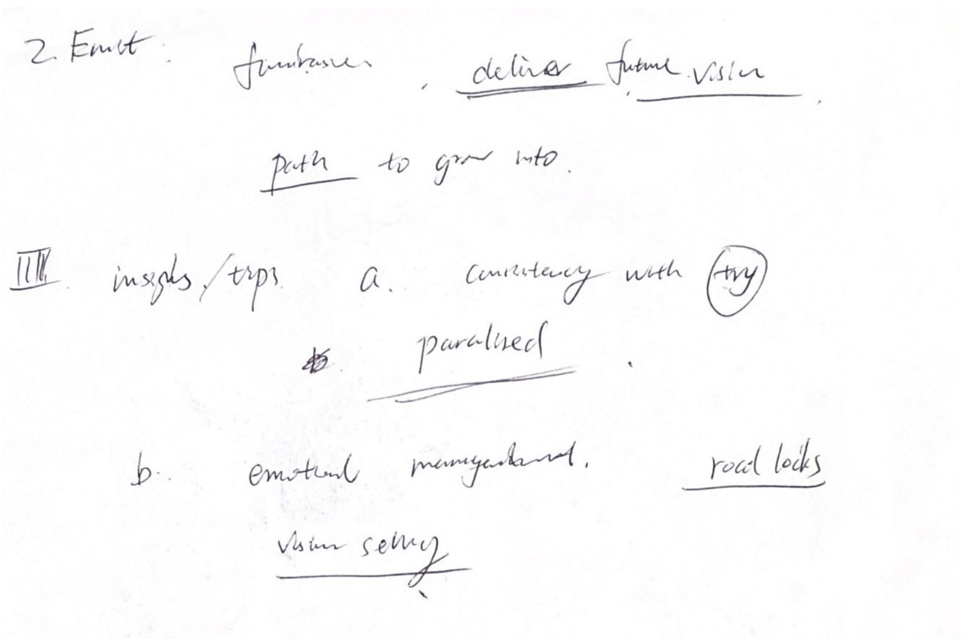
start from scratch, Apple Samsung. stand on the shoulder of giants

III Business. rule of leadstarts, platform

tools to manage time. running ~~off~~ out of time

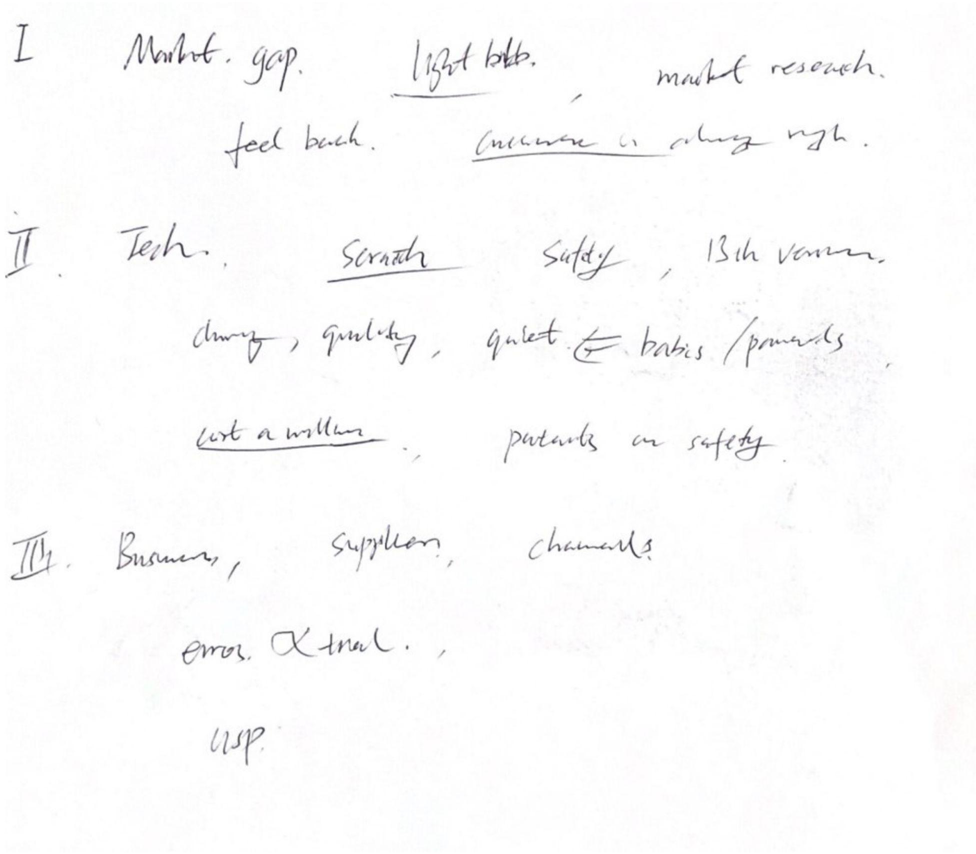
vote for confidence, matrix to focus on.

tribe (people group). hyper busy.


2. Emot. fundraise, deliver future vision.
path to grow into.
III. insights / tips a. consistency with (try)
paralised.
b. emotional management, road locks
vision setting

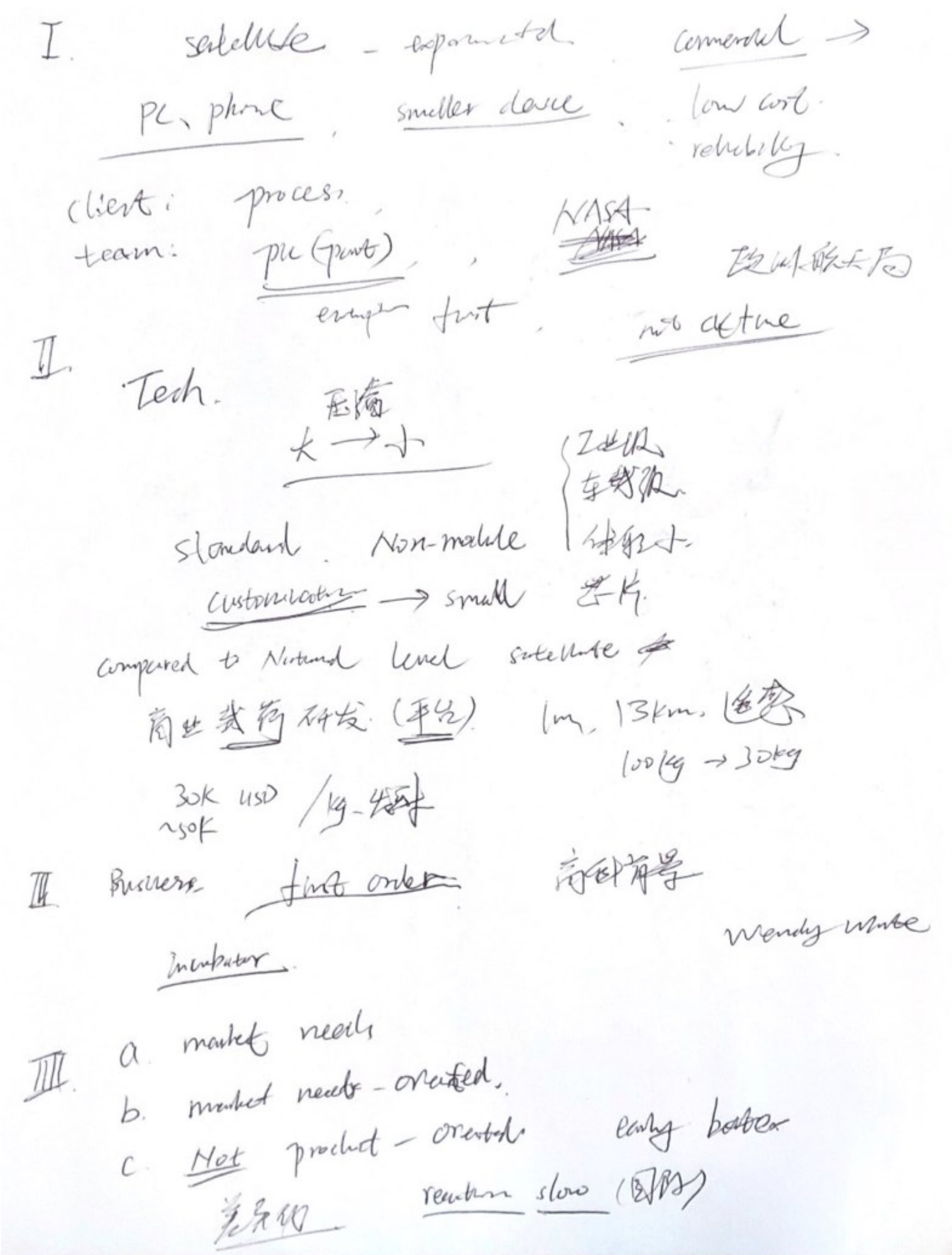
3. SME-C

SME-C is the world’s first baby mattress that helps the baby fall asleep in the baby’s own bed using a combination of technologies. The award-winning design produces a gentle, automated up-and-down movement which is similar to in the parents’ arms or in the womb. The mattress helps to boost a baby’s sleep and therefore release the parents from this challenging task for improved parenting experience. The mattress is expected to reduce SIDS (Sudden Infant Death Syndrome) by monitoring data on health including sleeping patterns, breathing and heart rate, and oxygen saturation, etc.


I Market. gap. light bulb. , market research.
feed back. Customer is always right.
II. Tech. Scratch Safety, 13th version.
change, quality. quiet ⇐ babies / parents,
cost a million. patents on safety.
III. Business, suppliers, channels
errors. & trial. ,
USP.

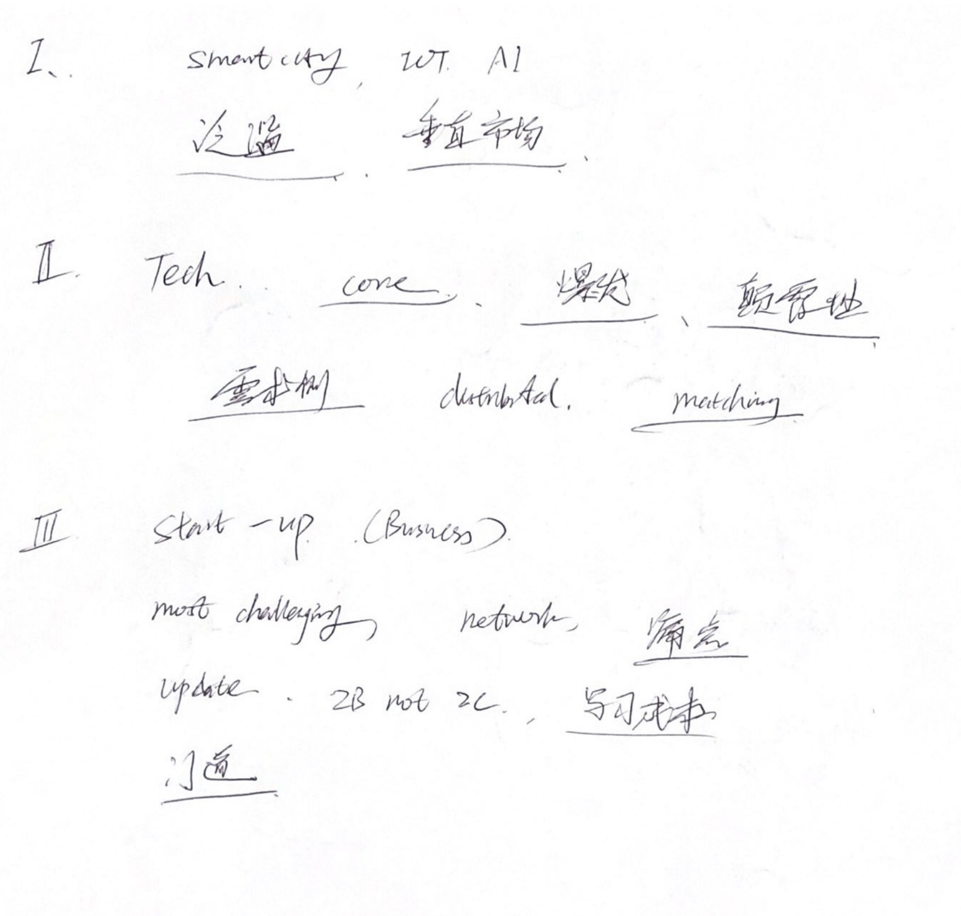
4. SME-D

SME-D is a space mission provider by offering microsatellites, mission design, in-orbit operation, lauching brokering and regulatory services. With the goal of ‘small satellite, big capability’, the innovate satellite technology is developed in house and open to cooperation with partners globally. The aim is to deliver the most advanced satellites while significantly reducing the cost to approximately 10 percent of the traditional satellites.



5. SME-E

SME-E is an UK energy technology startup with the goal of using IoT and AI technologies to deliver ubiquitous energy solutions to address the challenges faced in the energy industry. The intelligent distributed energy balancing and trading platform provides localised balance, flexibility and transaction services. Distributed assets such as building flexibility, electric vehicle charging and energy storage systems become power-responsive virtual power plants. The main features of the platform include: 1) Promote the participation of consumers in the wholesale electricity market, including ancillary services and balancing market; 2) Peer-to-peer energy trading platform and trading between self-organising consumers; 3) The automated system matches consumers with similar preferences, including environment, risk, community interest, location and time, etc.



6. SME-F

SME-F is an OEM of industrial automated additive manufacturing machinery with the world's first hybrid and automated industrial AM machine for mass production of metal and polymer parts. Integrated with the dedicated IoT software for remote control and production optimisation, the system is capable of manufacturing 24/7 with minimum human intervention, which reduces the final cost per part to accelerate the uptake of additive manufacturing by the industry. The vision is the use of the complete power of 3D Printing to industrialise additive manufacturing through an integrated end-to-end process.

I. with industry, machine, Spain.. mass + 3D printing

~~industry to adopt~~. work with customers first,

university. lack of 3D industrial app., research

automated. closed the gap.. European [illegible]

horizon 2020, roadmap, ① mass, ② metal. followers

③ automated

open software.

II Technology, metal, 10 systems validate.

all industry, bear of standard.

III. 2016; 2018. 第一台: 8 in team.

from nothing. hardware, software, system.

networks of customers.

7. SME-G

SME-G Healthcare focuses on the ultra-high definition medical endoscopy imaging system and digital integrated operation room solutions. Based on original image processing algorithms and real-time implementation of FPGA platform, a complete professional solution for medical imaging applications has been developed, including high-quality chipset, 3D and 4K endoscopy devices. Digital integrated operation room solutions with enhanced features are also designed for various hospital criteria. Intelligent medical devices based on AI and FPGA is currently under development with Chinese Academy of Science, which is expected to improve the performance of the imaging devices for ophthalmology and pathology.

I. Market Gap, Edscape.

monitor to start, no specific needs, too expensive

added value, quality, lack, low completion

closed up/sealed up, requirement ↑.

example, experience = different. No training opportunity.

小闭环,

II Tech core, confidence score,

starting point of race, support

III high speed → high quality, [illegible].

附加值.

Business. → not good start, ——

路径、包子 变，[illegible] 内功

梦想，设定 一窝蜂.

8. SME-H

SME-H innovates the underlying technologies for XR and Robotics using VSLAM and multi-sensor fusion. Its high-speed, high-precision XR Vision and Robot Vision products have won numerous awards and recognitions globally, including CES 2019 Innovation Award, Top 10 Machine Vision Solution of 2018 Award and Disruptive Technology Award. The developed solution has been widely adopted in the fields of AR/MR HMD, robotics, and drones for its superior tracking capacity.

I. outside in — 12 — 17 — inside out

人眼双目定位　视场角　左右150°　上下120°

VR, AR, Robotics (激光), 快递 (GPS, UWB,) 派送小车 (磁道) 扫地机器人 识别

II Tech. 精度、功耗、电池续电、60FPS 1000FPS

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Appendix 7. Example lubrication solutions from analogical thinking

The preliminary lubrication solutions as the result of analogical thinking reported in Chapter 8 are described in detail as follows.

a. Engine oil

A typical type of engine oil consists of a high quality synthetic base fluid and multifunctional additives, the combination of which offers a lowered friction coefficient, rapid anti-wear film formation which is thus highly wear-resistance. Oxidant inhibitors and corrosion inhibitors are blended in to limit detriments to engine parts. Premium additives, such as detergents and dispersants, keep engine clean and extend its lifespan. Other additives, such as viscosity index modifier, foaming inhibitors and extreme pressure additive etc. provide the engine with maximum protection under various working conditions.

A typical operating condition for engine oil could be:

- 100°C
- 1 GPa
- 0.05 m/s (boundary lubrication)
- 50% Slide-to-roll ratio (SRR)

b. Aircraft gas turbine oil

The application of SLP offers a better understanding of the unique requirements of aircraft gas turbine and assists the customisation of suitable lubrication solutions to fulfil working conditions such as:

- High viscosity index synthetic base fluid
- Thermal and oxidation stability
- Load carrying
- High temperature corrosion resistance
- Low volatility
- Performance at -40°C to 40°C
- High flash point, flame point and auto-ignition point

c. Hydraulic fluid

This complex hydraulic fluid is designed to transfer energy and pressure, remove heat, reduce wear and protect the machinery from corrosion. Its main characteristics are:

- Thermal stability
- Hydrolytic stability
- Low chemical corrosiveness
- High anti-wear properties
- Low tendency in cavitation
- Long life span
- Total water rejection
- Constant viscosity at various temperatures

d. Multipurpose automotive oil

The multipurpose automotive oil can be applied to automotive suspension, steering system and braking system. As this type of oil will be exposed to various environmental conditions such as temperature, mud, rain, dust, road salt and snow, as well as a variety of driver-controlled vehicle operating conditions, it thus needs to provide the following guarantees:

- Outstanding oxidation resistance and mechanical stability
- Protection against corrosion by water and salt water
- Resistance to water washout
- Excellent wear protection under conditions of loading and movement
- Some sealing against the entrance of dirt, water and other contaminants
- Resistance to pounding, leaking and squeezing
- Friction-reducing capability to decrease steering effort and provides smooth riding characteristics

e. Industrial gear oil

Industrial gear boxes are becoming smaller and lighter yet more durable, leading to greater demands on the use of high-performance base fluids and additives. This product is specially designed for lubricating industrial gears that are exposed to high pressure and a wide range of temperatures, thus it needs to provide:

- Excellent extreme pressure and anti-wear properties
- Good mechanical stability and operating reliability at different temperatures
- Good anti-corrosion properties
- Non-staining to yellow metals
- Improved gear efficiency and reduced noise generation
- Increased lubricant service life

f. Transmission oil

A highly specialised type of transmission oil is designed to transfer heat, lubricate gears and transfer power in transmission systems. The viscosity of this transmission oil is critical at both a high and low temperature to optimise performance. Friction behaviour is taken into careful consideration as they greatly affect the efficiency and the friction durability of the transmission system. Oxidation resistance, EP/anti-wear properties are all well-controlled. At the same time, it is compatible with seals, different types of metals and plastics. Therefore, there are many (between 10 and 20) types of additives (10-20% of total content) in this transmission oil which provide all the aforementioned properties.