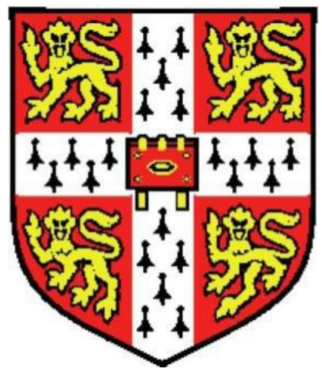
Search Strategies in Holistic Design Problems



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Doctor of Philosophy

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- To my parents -

- In loving memory of my grandfathers -

Declaration

This thesis is the result of my own research and does not include the outcome of collaborative work, except where stated otherwise. The dissertation has not been submitted in whole or in part for consideration for any other degree.

This document contains fewer than 150 figures and fewer than 68,000 words, excluding the bibliography.

Abstract

The research examines the search process of holistic design in three cases that differ markedly in their complexity, namely graphical design, small household appliance design, and automotive design. Design, as a creative activity, employs a *search* process because solutions cannot be found by optimisation procedures from input parameters. *Holistic* designs are characterised by the overall design performance arising from nontrivial interactions among many parameters, so no simple performance function can be described. Structured approaches, such as decomposition by customer needs or by technical systems, have proved to be "insufficient" in addressing such design problems.

Using data collected by in-depth interviews, the research compares the search approaches employed in the design process in these distinct industries. Similarities are found in the creative part of the search, where broad solution characterisations and starting points for the search are identified. However, in the experimental exploration of the solution space, the processes differ significantly between cases with different degrees of complexity, even though the search in all cases is built of the two fundamental building blocks of trial-and-error learning and selectionism. For example, the complexity in automotive design leads to the emergence of a highly rugged performance landscape, which requires diligent coordination of teams that search subspaces: Workers searching these subspaces are interdependent, and therefore they need to continually exchange information and adapt to one another.

The frameworks resulting from the comparison may help academics and practitioners to better understand design processes from a search perspective. The study may also help managers to decide on the required organisational capabilities and processes for developing products with different degrees of complexity. The thesis concludes by summarising the contributions that were made and suggesting future research opportunities to leverage the work that was initiated and embarked upon with this research project.

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Finally, I wish to acknowledge my parents for instilling in me the values of perseverance, integrity, and positivity, which have been indispensable in navigating life's various challenges.

Publications

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"There is much beauty in the superficial complexity of nature.
But there is a deeper beauty in the simplicity of underlying
process that accounts for the external complexity"

(Simon and Newell, 1970).

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1. Introduction

“Many problems can be modelled as search problem where one is required to find a path in a state space” (Thayer, *et al.*, 2012). Design problems are no exception; they have precisely the features that characterise search problems, e.g., uncertainty about the goal’s location, the adaptive varying of position, and a stopping rule. Hence, the design process can be considered as searching the ‘problem and solution spaces’, where designers employ a set of search strategies in order to achieve the ‘best possible’ or ‘good enough’ solution.

The term search strategy (adapted from Bates, 1979) can be defined as a series of concrete actions (steps) aimed at finding information (Laxman, 2010). The series of steps in design typically take the form of stages of increasing detail, for example progressing from conceptual design through embodiment design to detailed design (Pahl and Beitz, 1996), until sufficient information is available for the product to be manufactured.

Structured approaches are widely used in design, for example, decomposition by customer needs, or decomposition by technical systems that provide sub-functions of the overall desired function, combined according to the logic of constrained combinatorial optimisation (e.g., Suh, 1990; Pahl and Beitz, 1996). Such approaches help in reducing the complexity of the design problem and enhance the efficiency and effectiveness of the design process (Browning, 2001; Ulrich and Eppinger; 2008; Liikkanen & Perttula, 2009; Eppinger and Browning, 2012). However, these approaches are insufficient to produce high-performance, holistic designs, where performance arises in a complex way from most of their components (Ulrich and Ellison, 1999).

1.1. Gap in Knowledge

Despite the widespread acknowledgment of design as a problem-solving activity, there exists a significant gap in understanding how designers tackle holistic designs. In such systems, “the whole is more than the sum of the parts” (Simon, 1962); and the overall performance of the product is governed by interdependent parameters. Therefore, the overall design performance cannot be expressed “as an explicit mathematical function” or “can be made only partially explicit”. In addition, “performance of an individual component does not have meaning independent of the product context” (Ulrich and Ellison, 1999). Not surprisingly, the

success of a product (as a whole object) in the marketplace "may be determined by its aesthetic appeal, the pleasure it creates, and the satisfaction it brings to the customer. Emotions influence how a customer interacts with the product. In the interaction, feelings accompany thinking" (Khalid and Helander, 2006). Often, holistic designs demand not only functional efficiency but also elicit a strong emotional and subjective response from users.

The emotional response of humans to holistic design is also acknowledged in other areas of literature, e.g., in architecture design; Higuera-Trujillo, *et al.* (2021) note that "Humans respond cognitively and emotionally to the built environment". In product and service design Abbot (1955), argues "what people really desire are not products but satisfying experiences". Lemon *et al.*, (2016) add that customer experience is "holistic in nature, incorporating the customer's cognitive, emotional, sensory, social, and spiritual responses to all interactions with a firm". It is not sufficiently well understood how designers address holistic designs.

The literature abounds with models depicting the design process, yet there's a lack of depth in exploring how aesthetic considerations intertwine with functionality and user experience in the context of complexity. Establishing such understanding would provide insights into the processes that lead to innovative and high-performance product designs. It would help deciphering the intricate relationship between aesthetics, functionality, and emotional engagement, which plays a pivotal role in the success of products in the marketplace. Furthermore, it would offer an opportunity to advance design theory and practice, enriching the academic discourse on design processes, methodologies, and their impact on final product outcomes.

1.2. Purpose of the Study

Given the problem situation outlined above, the work described in this thesis aims to characterise and explain the 'search' process and behaviour of designers in solving 'holistic' design problems with different degrees of complexity. In holistic design, the performance is judged not only by functionality measures, but also by the emotional responses it triggers as a whole entity.

This thesis will primarily focus on the design of those groups of products with aesthetic dimensions as well as functional dimensions. It is important to acknowledge that holistic design encompasses a broad spectrum of considerations, including sustainability, usability,

and various contextual factors. The decision-making and problem-solving behaviours of designers are significantly influenced by the interplay between these dimensions. The decision to concentrate on aesthetics and functionality stems from the recognition that these aspects often form the core of design discourse and practice. This narrowing of the research scope enables the thesis to provide a concentrated and in-depth analysis of the interplay between form and function, aesthetics and practicality, in holistic design. This approach enables the thesis to generate insights and contributions that can serve as a foundation for future research, including the exploration of other aspects of design, such as sustainability.

The research is related to at least three streams of literature: design process, complexity theory and search in human problem solving, in which the last plays a significant role in the other two domains. The bodies of literature are also interdependent. Design has been considered as a problem-solving process (e.g. Goel and Pirolli, 1992); design of complex products has also attracted scholarly attention, in particular from researchers that study design optimisation and system engineering (e.g., Browning, 2001; Hobday, 2000; Pahl and Beitz, 1996). Complex problem solving is another domain that has been extensively researched for example by scholars in the field of Artificial Intelligence (e.g., Luger, 2009) or human cognition (e.g., Funke, 2010, Simon and Newell, 1971).

The starting point for this thesis would be to establish an understanding of the design process and the range of activities undertaken by designers in order to find a design solution; the literature presents a wide array of graphical models to represent the design process. Therefore, this research also encompasses a review of some of the most influential 'graphical models', which as will be discussed in chapter two, are a subset of qualitative approaches.

For the purpose of this research, it is also necessary to establish definitions of key concepts including design, search and holistic design. These will be discussed in Chapter 2. In particular, the term "holistic design," as employed in this thesis, carries a specific implication that extends beyond the process of designing itself. It pertains to the inherent nature of a design problem or solution, emphasising the interconnectedness and interdependencies among various design elements. This notion has not been widely articulated in the design literature, making it essential to provide a precise definition in the context of this research.

Hence, in chapter 2, first, the common meaning of “holistic” is discussed, and then the definition is further elucidated by comparing holistic against reductionist. Subsequently, reference to this concept in design literature is reviewed. In particular, Ulrich and Ellison's work on holistic customer requirements provides valuable insights into the complexities inherent in holistic design. Combining these references, "holistic design" in this thesis is defined as an approach that views a design solution as an interconnected and integrated entity, where the performance emerge from intricate interactions among multiple parameters and components. This perspective is characterised by the inability to express the overall design performance through a simple mathematical function, the non-independence of individual component performance, and the subjective and emotive nature of user preference.

It is also necessary to define what is meant by complexity, in the context of design. For this purpose, reference will be made to Stuart Kauffman’s NK Model (Kauffman and Levin, 1987; Kauffman and Weinberger, 1989). The model is not only one of the most influential contributions to complexity theory, but also provides a framework to elaborate on other concepts that are needed to be referred to for the analysis of this thesis. i.e.: search for problem-solving, decomposability and bounded rationality.

1.3. Questions

This dissertation seeks to explore and understand the design process through two fundamental hypotheses:

Hypothesis 1: Design is a type of search (which includes subjective evaluation of form and function);

Hypothesis 2: Complexity is the major driver that influences how the design search is implemented.

These hypotheses lead to two central research questions:

Research Question 1 (RQ1): How can we define and characterise design as a search process?

Research Question 2 (RQ2): What factors systematically influence the nature of design search, with particular attention to the role of complexity?

To comprehensively address these research questions, the following research objectives are outlined:

RO1: Provide an overview of what we already know from the literature about what designers do to find the design solution.

RO2: Explore understanding of search across different topic areas including Human Problem Solving and Design.

RO3: Investigate design process from a search perspective in practice and describe the findings in the form of conceptual frameworks.

RO4: Compare the empirical findings with existing literature and identify the gaps.

RO5: Identify and investigate elements that influence design search.

RO6: Compare the search processes (from empirical findings) using the identified contingency parameter.

Of which RO1-4 are closely related to the exploration of RQ1, providing insights into defining design as a search process, while RO5 and RO6 are focused on addressing RQ2, understanding the influential factors affecting the design search process.

Figure 1-1 shows a summary of the above and how the research questions and subsequent objectives have been addressed by the discussions in different chapters.

Research questions and Objectives	Chapter
RQ1: How can we define and characterise design as a search process ?	
RO1: Provide an overview of what we already know from the literature about what designers do to find the design solution.	2
RO2: Explore understanding of search across different areas including Human Problem Solving and Design.	2
RO3: Investigate design process from a search perspective in practice and describe the findings in form of conceptual frameworks.	3-6
RO4: Compare the empirical findings with existing literature and identify the gaps.	7
RQ2: What factors systematically influence the nature of design search?	
RO5: Identify and investigate elements that influence design search.	7
RO6: Compare the search processes (from empirical findings) using the identified contingency parameter.	7

Figure 1-1 Outline of the research questions and subsequent objectives.

2. Literature Review

This thesis presents an analysis of the extant literature in several key areas, including definitions and characteristics of design process and design process models (to justify why design can be considered as a search process), search in human problem solving (to understand search behaviour of human agents) and complexity and complexity theory (which is assumed in this thesis to impact the design search). However, prior to focusing on these topics, a wider range of literature in the field of design and development was reviewed to establish a broad understanding of the design research. These streams of literature, including on design strategy, design performance measurement and management, and design risk are not directly referred to in this thesis but have been influential in developing a better understanding of some of the key research streams in the field of design (for a novice design researcher) and ultimately, deciding on the scope of this thesis.

The strategy for searching and filtering the literature for review was as follows: The collection of publications was obtained from searches in major electronic databases like Web of Knowledge and Scopus completed with an open search using Google Scholar. For each part of the literature review, a range of keyword combinations was used. Once a paper proved to contain robust and relevant content, the list of its references was scanned to identify any additional literature. Considering the above criteria for the selection of publications over 400 items, including journal articles, conference and working papers, and books were selected for comprehensive review; a significant number of this collection are directly referred to in this thesis.

2.1. Defining Design

Providing a definition of design is a natural starting point for discussing it. Many scholars have given definitions of design; for an overview, see, for example, Hubka and Eder (1996); Banathy (1996), and Evbuomwan *et al.* (1996). However, the efforts to define design have not led to a commonly agreed definition. This is not necessarily a bad thing, and as stated by Buchanan (2001) this can be a strength that the community has not settled on a single definition; forasmuch as the fields in which definitions are settled matters tend to be lethargic or dying, "where inquiry no longer provides challenges to what is accepted as truth". At the same time, definitions are required for advancing inquiry, and this research is no exception.

The challenges to defining design are numerous; some are discussed in the remainder of this section.

The 'word' design itself presents definitional challenges (Ulrich, 2011). Heskett (2005) argues that the term design, although is common enough, "is full of incongruities, has innumerable manifestations, and lacks boundaries that give clarity and definition". This is partly because of the limitations of the English language and the fact that the 'design' refers to a variety of activities as well as the output of activities. To illustrate the confusion caused by many levels of meanings associated with the word design, Heskett (2005) gives a seemingly nonsensical example sentence:

"Design is to design a design to produce a design".

The study of design is also contextual and multidisciplinary. Design professionals work more and more in multidisciplinary teams in order to create an artefact. In a very simple form, a team of industrial designers and design engineers can be involved in creating a product. For industrial designers, design may mean to be more about creating the appearance, aesthetics, and ergonomics of the product; whereas design engineers may consider design to be more about creating the functional structure. Hence, differences in the disciplinary background (e.g., engineering design, industrial design, architecture, fashion design, etc.) give rise to some arguments. Design has also received scholarly attention from different scientific disciplines to name a few: cognitive science, system engineering, and computer science. Therefore, the body of literature presents numerous definitions of design; some are focused on a certain design discipline, some are more related to certain characteristics of design processes and others are more general (examples are given in Table 2-1).

Another challenge in defining design is due to its multifaceted nature. "There is no single way of looking at design that captures the 'essence' without missing some other salient aspect" (Lawson & Dorst, 2009). One of the other difficulties in understanding design is the "omnipresence of design or problem solving as a natural human activity" (Braha and Maimon, 1997). Design is present in much human activity for example an engineer making a kettle, a graphic designer creating a logo, a chef concocting a new pizza and a consultant configuring a new process.

Table 2-1 provides a few examples of different definitions of design from the reviewed literature. Definitions in the table below are compiled from a thematic analysis of the literature reviewed, where the terms such as "design is", "design is defined as", or "a design process include" were used as "keywords" for analysis. As can be inferred from the table of definitions, despite the breadth and diversity of views, there are yet sets of rules, principles and approaches underlying all design activities.

Alexander (1964)	The process of **inventing** physical things, which display new physical order, organization, form, in response to function**.**
Archer (1965)	A goal-directed **problem-solving activity**.
Banathy (1990)	"is a journey of creation. It is a journey toward a **desired future state**, which we define for ourselves and want to realize. Engaging in design we ask **questions similar to planning any journey**. Namely, (1) **Where are we now**? What is our present state? Why do we want to take the design journey?; (2) **Where do we want to go**? What is the future state we wish to attain?; and (3) **What route should we take** and what do we have to do to design the desired future state?" (Cited in Montuori, 2003)
Bruce & Bessant (2002)	"an application of **human creativity** to a purpose of **creating** products, services, buildings, organisations and environments which meet people's needs".
Buchanan (2001)	"the **human** power of conceiving, planning, and making products that serve human beings in the accomplishment of their individual and collective purposes".
Churchman (1979)	Primarily **a thought process** and communication process, transferring ideas into actions by communication.
Churchman (1987)	the **process** of putting together or relating ideas and/or objects in order **to create a whole** that hopefully achieves a certain purpose (cited in Braha and Maimon, 1997)
Daniel *et al.* (2007)	an observable domain which is comprised of "interwoven blocks that alternate in **'iterative' loops**. This is done until a **satisfying** design is found"
Goel and Pirolli (1992)	Design is "a **quintessential cognitive task.** The activity of design involves the mental formulation of future states of affairs. The products of design activity are **external representations of such possible futures"**.
Huang and Gu (2006)	"a screwy **evolution process** subject to **development constraints**"; in such a process design information transforms and accumulates.
Kesselring (1964)	"Designing mean to find a technically perfect, economically favourable and **aesthetically satisfactory solution for a given task"** (cited in Hubka, 1996).
Mostow (1985)	'an important **human** activity', a 'psychological phenomenon' and an 'interesting' kind of complex problem-solving.

Restrepo & Christiaans (2004)	**“a unique type of problem-solving”**, “the maximum expression of human intelligence and the prototypical case of cognition, as it requires devising future states of the world (goals), recognizing current ones (initial states) and finding paths to bridge both (transformation functions)”.
Schön (1990)	“the execution of **cognitive actions upon information”.**
Simon (1996)	“**description of an artifice in terms of its organization and functioning** – its **interface** between inner and outer environments”.
Ulrich (2011)	“conceiving and **giving form** to artefacts that solve problems”.
Ulrich (2011)	“Design is **an information processing activity** through which a plan for an artefact is created to address a gap in the user experience”.

Table 2-1 Definitions of design

What is conceived from these definitions and what seems to be more relevant to the scope of this thesis, is that design is a human problem-solving activity (and hence a cognitive action) with the aim to create satisfactory form and function in a unified artefact. As Ulrich (2011) states, the form does not necessarily mean geometric form, but other sorts of arrangements such as a nested list of symbols in a computer program. Considering design as human problem-solving activity is consistent with the information processing view of design, as articulated by Herbert Simon in his book Sciences of the Artificial, first published in 1969 (3rd ed. 1996). The essence of this view as stated by Ulrich (2011) is that *“design is a human problem-solving activity beginning with a perception of a gap in a user experience, leading to a plan for a new artefact, and resulting in the production of that artefact”.*

Another perspective on the design, which is of interest to this thesis, is the process of creating *a whole* to achieve a certain goal. The process of creation of the whole out of parts and the way a designer or the design team evaluates the design at different stages of the process to form a unified artefact, as well as the way such *entirety* is perceived by the customer is also related to the scope of this thesis. To create a whole, Ulrich (2011) argues that almost always, the first evaluation of a design is a cognitive response of the designer to a sketch or other representation of the design. He notes that “these evaluations are holistic judgments based on highly abstract descriptions. These judgments are efficient, but because they are formed rapidly based on limited information, they are plagued by uncertainty. Subsequent evaluations of more refined designs may be more analytical and may be based on a decomposition of the overall quality of an artefact into several dimensions or attributes”.

Similarly, Crilly *et al.* (2004) argue that, in the perception of products by consumers, their cognitive response to the form and the visual appurtenance of the products plays a significant role. They acknowledge that "product form may provide for unarticulated consumer requirements and suggest product qualities that are otherwise difficult to ascertain".

To summarise the above, this thesis uses the following definition of the design that also reflects the scope of interest of this dissertation:

"Creation of solutions to problems which are functional and aesthetically pleasing".

The above definition embeds in itself those characteristics of design that are relevant to the scope of this research. However, it should be noted that by adopting this definition this thesis focuses exclusively on the design of products with aesthetic dimensions.

2.2. Characteristics of Design Processes

Understanding the characteristics of the design process is essential in developing proper process models and appropriate tools to support decision-making activities. Some studies discuss the typical characteristics of the design and development process. For example, Fricke *et al.* (1998) listed several characteristics that can be used to describe the development process including: "creative and innovative, dynamic, interdisciplinary, strongly interrelated, strongly parallel, iterative, communication-intensive, anticipatory, planning intensive, uncertain, and risky". Zu and Huang (2004) consider design to be phased-based, hierarchical (in terms of tasks and subtasks) and iterative. In a more in-depth study of the characteristics of the engineering design process, Maier and Störrle (2011) extracted 18 attributes from the literature and personal experience and classified them into six areas of challenges for process modelling in the engineering design domain. The area of challenges included: development (in terms of complexity and ambiguity of process), collaboration (related to interdependencies and interactions between processes, people and organisation), products and services (resulting from constraints imposed by physical rules, legislation and economic/market constraints), formality (related to the need for automated support, conceptual clarity and formal semantics), pragmatics and flexibility both arising from the realm of modelling rather than an application domain.

This section presents a list of seven design process characteristics that arose from the thematic analysis of the literature review. While not exhaustive, it aims to incorporate various characteristics identified in the previous studies. For example, ‘communication intensive’ may stem from the social and collaborative nature, and ‘dynamic and interrelated’ from the evolutionary and concurrent nature of design processes. These characteristics will be further examined in this chapter, discussing their implications on modelling and managing the design process.

2.2.1. Creative and Intuitive

The role of human intuition in developing creative solutions to design problems has been noted by many scholars. For instance, Ertas and Jones (1996) emphasise that intuition largely arises from accumulated knowledge stored in the brain, accessed by engineers when addressing new design challenges, ideally leading to concept formulation through the synthesis of pertinent past experiences. Finger and Dixon (1989) argue that highly creative systems involve knowledge acquisition and knowledge control at different levels of abstraction. These perspectives align with a design paradigm that sees design as an art, emphasising learning through practice rather than analytical deconstruction. The analytical methods of design, which break it down into subsystems and components, may be considered to be of no relevance from this perspective. However, while well-qualified design teams are crucial for project success, the significance of employing structured methods to enhance design performance is undeniable. While the literature describes many systematic approaches that can be applied to different elements of a design process, it seems this question is still unanswered: what is the right balance between the use of intuition and structured approaches? In addition, the intuitive and knowledge-based characteristics of the design process impose challenges in modelling the design process, as representing intuition in a model, and balancing it with scientific tools is difficult.

2.2.2. Iteration

Daniel *et al.* (2007) describe design as an observable domain comprising "interwoven blocks in iterative loops until a satisfying design is found" (cited in Sharafi *et al.,* 2010). Huang and Gu (2006) define the design and development process as a dynamic feedback-based system, with iteration and feedback as integral components. According to Dym *et al.* (2009), iteration

and feedback are adaptive characteristics in the design process as the solution to a design problem evolves.

Feedback involves providing information about process output to enhance results. Dym *et al.* (2009) identify two types of feedback in design: internal feedback loops during the design process to verify performance and external feedback after-market release to validate design success.

Iteration implies analysing multiple trial systems sequentially until an acceptable design is achieved (Arora, 2004). Osborne (1993) distinguishes between anticipated iteration, an expected response to new information, and unanticipated iteration, caused by internal errors or shifts in product strategy (Smith and Eppinger, 1993).

One key consequence of iteration is rework, which accordingly increases design lead time. The cyclic nature of the design process associated with testing, analysing and feeding back information and refining design is shown in Figure 2-1, proposed by Khandani (2005).

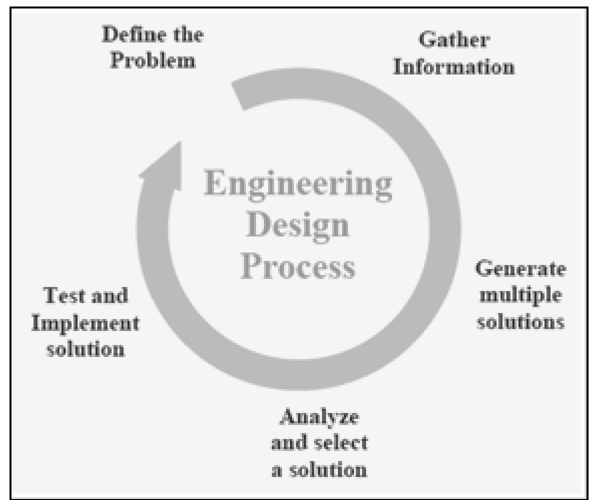

Figure 2-1 Iteration in the design cycle (Khandani, 2005)

It is argued that iteration is one of the key characteristics of a design process that cannot be fully reflected in a mechanistic model (Wynn *et al.,* 2007). While anticipated iteration can be planned and be incorporated in a model, unanticipated iteration presents modelling difficulties.

2.2.3. Concurrency

Design and development processes are defined as the process of transforming needs into a technical and commercial solutions by numerous scholars (e.g., Whitney, 1990; Huang and Gu, 2006; Churchman, 1979). "During this transformation process, the design engineer makes decisions about many engineering attributes (e.g., function, structure, shape, strength, material, economy, regulations, etc.) in a concurrent manner" (Nahm and Ishikawa, 2004). Concurrency in design process is a well-known approach for reducing the time-to-market, improving quality, decreasing manufacturing costs, and improving customer satisfaction (Lawson and Karandikar, 1994; Prasad, 1999; Willaert *et al.,* 1998).

Blackburn *et al.* (1996) differentiate time and information concurrency: Time concurrency involves parallel activities by different individuals or groups, while information concurrency concerns the extent of information sharing (Cited in Loch and Terwiesch, 1998). Yassine *et al.* (1999) distinguish between parallel and concurrent task execution, highlighting that concurrent execution encompasses not only task start timing but also the frequency and richness of information transfer between tasks. In a global automotive industry study, Clark and Fujimoto (1991) found that companies achieving faster development times overlapped activities and fostered frequent, bi-directional information transfer, terming it "integrated problem solving.

Figure 2-2 depicts a schematic comparison of sequential and Concurrent design, developed by Yazdani and Holmes (1999). The comparison reflects the reason for the attractiveness of concurrent design to companies. However, what is not reflected in this diagram is the fact that CE can potentially reduce the length of each activity as well as the lead time.

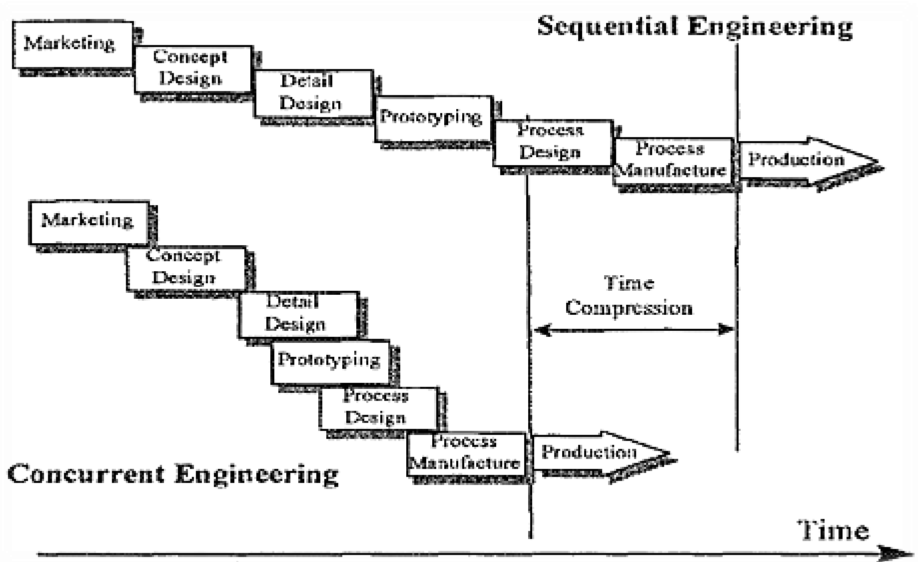

Figure 2-2 Concurrent and sequential engineering (Yazdani and Holmes,1999)

Empirical studies by Eisenhardt and Tabrizi (1995) and Terwiesch *et al.* (1996) show that CE may not be suitable for all projects due to risks of rework caused by inadequate information exchange. Nahm and Ishikawa (2004) argue that "since CE philosophy is intended to consider all elements of the product life cycle from the outset, CE approach increases the complexity of design problem and makes it more difficult to manage". Cordero (1991) suggests using concurrency only in projects with modest technical uncertainty and Loch and Terwiesch (1998) propose that concurrency should be employed when the gain from overlapping activities outweighs the delay from rework that results from proceeding in parallel based on preliminary information.

The literature puts forward several modelling approaches for managing and implementing concurrent processes (e.g., Krishnan *et al.*, 1997; Fricke *et al.*, 1998; Loch and Terwiesch, 1998; Nahm and Ishikawa, 2004). The common aims amongst most of them are to improve the coordination of concurrent activities and/or help in evaluating the optimum overlap between activities.

2.2.4. Co-Evolution

In the design research, the term "co-evolution" finds widespread usage in elucidating the dynamic interaction between problems representations and solutions throughout the design process. Historically, researchers in design have frequently drawn comparisons between these processes and similar phenomena observed in biological evolution (e.g. Steadman,

1979; Basalla, 1988; Dasgupta, 1991; Vajna, et al., 2000). The foundational role of the biological analogy in design co-evolution is significant, providing a conceptual basis for comprehending the evolution of ideas within the context of design processes.

In the traditional view to design evolution, the design process shows a gradual evolution through its lifecycle from problem statement to design concept and finally the design solution. Borrowing a term from biology Dasgupta (1991) named this type of evolution as 'Ontogenic design evolution', which as per his classification refers to the design processes that share characteristics of observed evolutionary phenomenon and "occurs between the time when a problem is assigned to the designer and the time the design is passed on to the manufacturer". Throughout this period, the design evolves from an initial state to an acceptable form. In this situation, one can say that there is an adequate fit between the design and the requirements. However, as highlighted by Maher *et al.* (1996), this view "assume designers work with a well-defined problem". They note that in practice, the development process does not simply move from the problem to a solution, as the required information is mostly incomplete and unstructured. The ill-defined nature of design problems leads to the concept of 'co-evolution'. They define the concept of co-evolution as "the stepwise increase of knowledge about the addressed problem parallel to the developed solution, i.e.*,* the product" (cited in Eisenbart, *et al.*, 2011). In other words, in the journey of searching for the possible solutions to the design problem, certain constraints and features of the potential solution may result in exploration and the redefinition of the problem specification. Therefore, the problem and the solution can co-evolve. They present a formal exploration model depicted in Figure 2-3, illustrating the interaction between two distinct search spaces: the problem space (P) and the solution space (S). This interaction leads to the gradual evolution of both spaces over time, where each space's evolution is influenced by the most recent population in the other. In this model, horizontal movement signifies an evolutionary process in which the problem space (P) and solution space (S) progress over time. Diagonal movement represents a search process where goals lead to solutions, indicated by either a downward arrow (from problem to solution) or an upward arrow (from solution refocusing the problem).

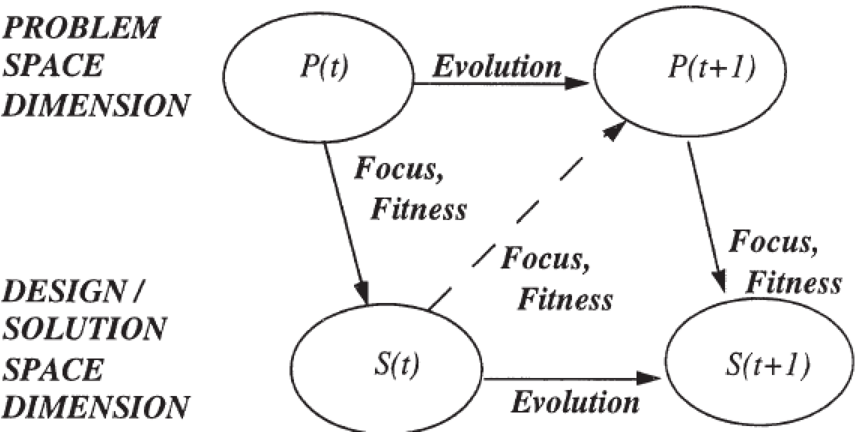

Figure 2-3 Problem-design exploration model (Maher et al., 1996)

Dorst and Cross (2001) subsequently replicated and adapted Maher *et al.*'s diagram. In their exploration of creativity in the design process, they conducted a protocol study with experienced industrial designers responding to a brief. Their findings indicated that designers did not perceive the design assignment as a static "design problem" but consistently employed dynamic manipulation, thereby reinforcing the validity of Maher's model.

In 2019, Storm, *et al.,* introduced a structured model for the design process, encouraging design students to consistently reframe their problem space. This model incorporates the co-evolution concept and introduces novel elements like manifestation, goal, and methods, with the specific intent of enriching the representation of coevolution in the design domain. The model explicitly showcases how these integral elements contribute to the co-evolution transitions between problem and solution spaces. The inclusion of these additional elements extends Maher & Poon's (1996) co-evolution model, specifically tailored to support framing in the design process. The findings extend the discourse on the importance of co-evolution in the design context by emphasizing the role of methods and design manifestations in facilitating transitions within and between spaces. This aligns with previous studies (Stompff *et al.*, 2016; Cash & Goncalves, 2017) highlighting the significance of surprises, knowledge sharing, and information exchange in the reframing process, now broadened to include tangible design methods and manifestations such as sketches or presentations."

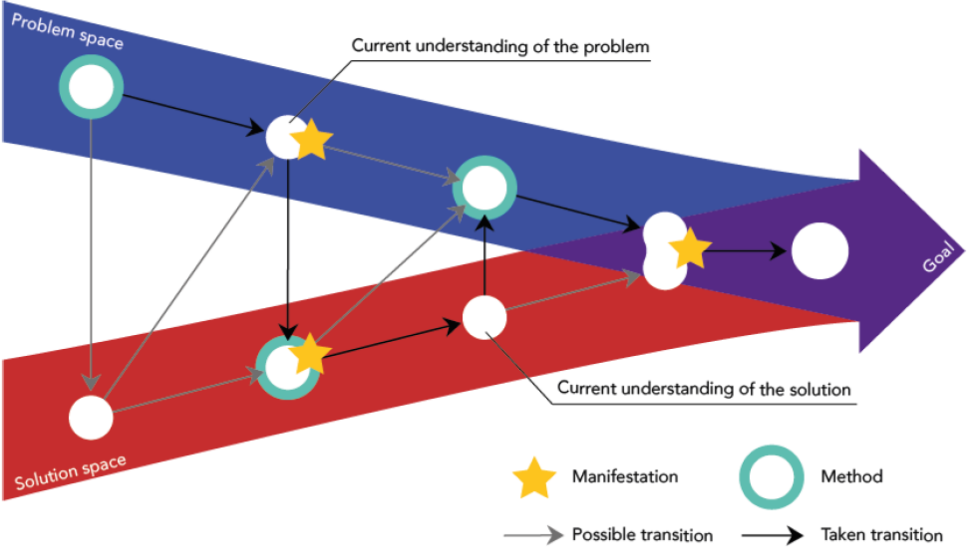

Figure 2-4 Refined model of framing (Storm et al., 2001)

Jun and Suh (2008) argue that in the traditional perspectives on design evolution, the role of change propagation has not been explicitly considered. However, in general, the output of design activities materialised as engineering specifications, drawings, and technical calculations are unstable because a design change may create a chain reaction of changes in data of other activities. Therefore, there is also an evolutionary feature in design activity resulting from change propagation (Jun and Suh, 2008).

Figure 2-5 is an effort to reflect a combination of these perspectives to design evolution. As depicted in this figure, design can be considered as a continuum of steps, each consisting of a problem-solution pair. The problem space and the solution space coevolve together as a result of decreasing the ambiguity regarding each space (which is represented by shrinking the size of rectangles) and the exchange of information between the spaces. Ideally, through this coevolution, the misfit between design and requirements should diminish until a satisfactory fit between design and requirement is achieved. It should be noted that one could always enhance a design in order to reach a better fit. The representation of the reflective evolution of design resulting from change propagation in the following diagram is somehow problematic. However, this can be presumed as the change in the spatial position of the solution space, which will generate a non-alignment between solution-problem spaces. This is represented with dashed line rectangles, which indicate the rectangles can move in the

respective space. Resolving such non-alignment then requires a new state of adaption and problem-solution positioning.

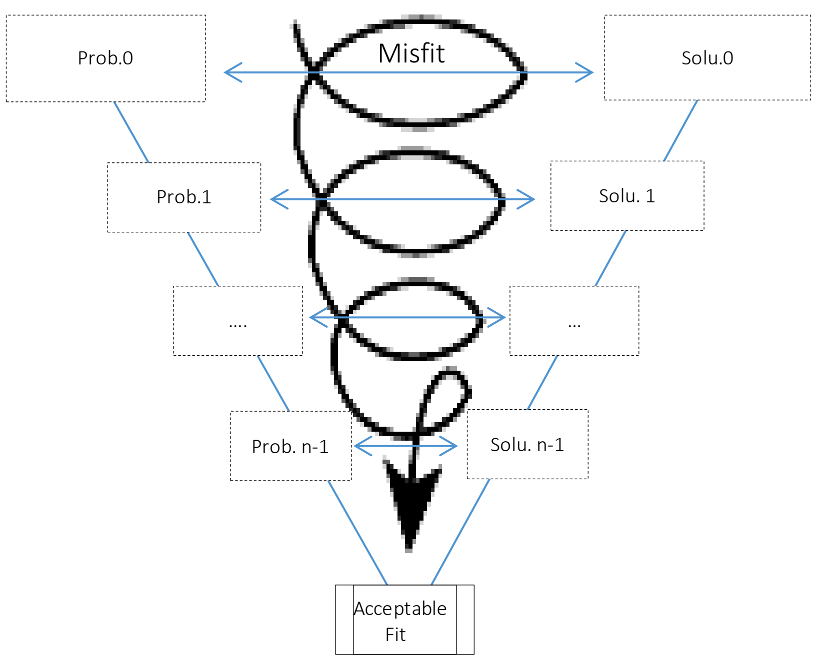

Figure 2-5 Design evolution

The evolutionary feature of design may lead to the overlap, or concurrency of activities in a process. However, many modelling techniques, do not allow the representation of this characteristic, because as stated by Jun and Suh, (2008) “they implicitly assume that design information can be finalised and transferred only after the completion of an activity".

Crilly (2021) underscores a surprising disconnection in the design literature from the rich biological analogy, hindering the exploration of co-evolution in design. He extends the biological analogy in contemporary discussions of co-evolution, providing a foundation for proposing expansions to the design co-evolution concept. Crilly refers to the notion of "diffuse" co-evolution, contrasting it with the traditional "pairwise" co-evolution, examining the relationships and developments observed in multi-species interactions. He suggests that taking this broader perspective allows for the consideration of co-evolution in various typologies, such as the co-evolution of design concepts and knowledge in "C-K" theory or the co-evolution of functions, behaviours, and structures in "FBS" ontologies.

In summary, Crilly's exploration goes beyond the binary relationship of problems and solutions, suggesting a wide array of co-evolving elements, including processes, knowledge,

concepts, functions, behaviours, and structures. The incorporation of ecological analogies, reflecting mutualistic co-evolution in nature, becomes relevant, enriching the understanding of the multifaceted nature of design evolution.

2.2.5. Uncertainty and Risk

Design is considered a process with uncertainty in outcome (O'Donovan *et al.*, 2003). This can be due to a range of reasons including "unpredictability of the environment, inability to predict the impacts of environmental change, and inability to predict the consequences of a response choice" (Wang *et al.*, 2010). The iterative nature of the design process means that solutions proposed at different stages are provisional, largely due to gaps in information. As the design process unfolds, an evolution in both the problem and solution spaces occurs, driven by their interplay and feedback mechanisms. This dynamic process facilitates a gradual refinement of solutions, enhancing precision and reducing uncertainties as one moves closer to an engineering resolution.

The importance of managing uncertainties and associated risks to boost the success rates of design projects is well-documented. Loch (2000) posited that managing a project should focus more on mitigating uncertainties rather than strictly adhering to milestones and product features. Risk management is one of the key approaches that have been widely applied in practice for managing uncertainty in design projects (Williams, *et al.,* 1995; Keizer *et al.*, 2002; Cooper, 2003).

The majority of existing design process models do not explicitly represent uncertainty. However, the literature shows some attempts to develop modelling tools for visualising and managing the uncertainties in design processes (e.g., Clarkson and Hamilton, 2000). Yet, it should be noted that the capture of all elements of, and influencing factors on the design process in a model is not possible; both because of the time it would take to record the elements that can be identified, and due to the impossibility of recognising the full set of important factors (O'Donovan, *et al.,* 2004). Hence, any model of design will be a partial model and the implications of working with such a model should be accounted for.

2.2.6. Collaboration and Social Interaction

Mostow (1985) defines design as ‘an important human activity’, a ‘psychological phenomenon’, and an interesting kind of complex problem-solving.

Alexiou and Zamenopoulos (2008) describe design as “a capacity derived from the distribution and organisation of complex socio-technical systems”. Sebastian (2005) mentions that the actual complexity of a design project results from the social difficulty, technical difficulty, and uniqueness of design.

The complexity of the products and their functionalities requires collaboration and coordination of experts from various disciplines and organisations resulting in complex relationships among both people and tasks. Malone and Crowston (1990) provide a useful definition of coordination as ‘‘the act of managing interdependencies between activities to achieve a goal’’. This definition highlights interdependency as a key concept underlying coordination. “There is indeed a variety of different interdependencies present in a complex task, including those arising due to shared resources and tasks, time constraints, or task–subtask relationships” (Alexiou and Zamenopoulos, 2008). It is not only the collaboration and coordination of different people that makes design a social process. Indeed, design is an intrinsically social process from another perspective: “Design products are motivated by and realised within a social environment” (Alexiou and Zamenopoulos, 2008).

Apart from the complexity associated with the variety of people and organisational structure involved in a design process, the complexity associated with the technical issues is a matter that has been discussed in the literature (Alexiou and Zamenopoulos, 2008; Smith and Morrow, 1999). However, "the new phenomenon in real-world practice shows that social complexities in design have been escalating on top of the technical ones. While new technological inventions can solve almost any technical difficulty, a new demand has arisen for the socio-psychological approach to manage socially complex design collaboration" (Sebastian, 2005)

The collaborative nature of the design process brings with it certain challenges in terms of managing the design projects. These include coordination of expertise, and resources, exchange of information and achieving a common understanding of the problem. In addition, the fact that product development activities are carried out by engineers of several teams

means that “there are numerous branching and merging operations for analysing and synthesizing their outputs" (Jun and Suh, 2008). Such characteristics cause complications in representing the design process with traditional modelling methodologies.

2.2.7. Complexity

“PD can be described as a complex web of interactions, some of which precipitate a cascade of rework among activities” (Browning and Eppinger, 2002). However, the complexity of design and development processes does not only result from being highly interconnected or including feedback loops and rework. The complexity can relate to the actual technical complexity of the engineering products which accordingly leads to the need for collaboration of numerous participants from diverse teams and organisations "resulting in complex relationships among both people and tasks" (Yassine, 2004). Therefore, product development of large-scale systems is a complex process both due to the technical issues that need addressing and the variety of people and organisations that need to be involved in a design project. The complexity of a design project can also result from the uniqueness of design projects (Sebastian, 2005) and its chaotic nature in the sense that the evolution of two seemingly equal starting states may result in two evidently different states after some time.

The design activities have also numerous objectives and constraints which can add to its complexity (Jun and Suh, 2008). The required amount of information transfers and data processing also brings another element of complexity to the design process. To this end, one can add the complexity of understanding users' needs and defining the problem.

As evident from the discussion above, the complexity of design stems from various characteristics of the design and development processes, such as social interaction, concurrency, and iteration. These interdependencies should be considered when developing tools and methods to manage the design process.

2.2.8. Concluding Remarks

The factors discussed above can describe the key differentiating features of design processes from day-to-day operational business processes. From the discussions it was evident that some of these characteristics are interrelated, e.g., complexity of the design process can result from, and lead to, iteration, concurrency, collaboration, and social interactions.

Therefore, there is scope for further refinement of this list and investigation of the interrelationships and exclusivities of the above-mentioned characteristics.

The implication of each characteristic in terms of modelling and managing design processes was also discussed. Understanding these characteristics is necessary for the development of appropriate tools and methods and the evaluation and selection of tools for application to real-world design problems.

2.3. Theories and Models of Design

In this section, some of the theories and models of design are reviewed. The thesis purposefully distinguishes between theories and models of design; as it appears that in the design community, the two words are commonly used interchangeably, whereas, in some other disciplines like operation management, each term conveys its own conceptual meaning. Discussions from the literature are presented below highlighting the difference between models and theories.

Models are system definitions without truth claims, used for conceptual exploration. Theories consist of law-like statements making assertions about the world and can be tested. Model building can be detached from theory, allowing scientists to explore models independently of their connection to reality (Hausman, 1992). Models can be verbal, graphical, or mathematical representations of phenomena that can be formulated after conducting extensive observations. Models can also be seen as an application or representation of theories in some instances. As such "theory" has a higher normative status than "model" and does not necessarily require a "model"; besides a "model" is not sufficient for a "theory" (Goldfarb and Ratner, 2008).

Table 2-2 shows distinctions between models and theories as stated by Daniel Hausman (1992) and adopted in this thesis.

Models	Theories (Descriptions, explanations, predictions)
definitions of predicates, concepts, or systems	sets of law-like assertions
trivially true or neither true nor false	true or false
point is a conceptual exploration	point is to make claims about the world

assess mathematically or conceptually, untestable	assess empirically testable
consist of assumptions	consist of assertions

Table 2-2 the distinctions between models and theories (Hausman, 1992)

While the design literature presents hundreds of models of the design process, indeed theories of design are limited. The most well-known and highly cited theories of the design are reviewed later in this chapter. In addition, To justify the inclusion of specific models in the thesis literature review, below various modelling taxonomies are reviewed. This clarifies the thesis's stance on model selection.

2.4. Modelling Taxonomies

A model is an incomplete representation of reality, an abstraction, which is built, verified, analysed, and manipulated to increase understanding of that reality (Buede, 2000). A useful model supports making predictions and testing hypotheses about the effects of actions in the real world, where such actions would be too disruptive or expensive to try. Such a model helps make insights otherwise available only through experience (Browning *et al.*, 2006).

"Models are useful means of understanding and interacting with both products and processes" (Eckert and Stacey, 2010). Concerning the value of models in understanding and analysing processes, significant attention has been paid to the development of process models. The goals of process modelling are several; including learning about the process, identifying ways that a process can be controlled, managed or re-engineered (Smith and Morrow, 1999) and organising multifunctional teams to develop products in a concurrent and cooperative manner (Huang and Gu, 2006).

Process models are known to be the central element of design methodologies (Gericke, 2011). Existing design literature presents a range of modelling approaches starting from very high-level representations down to more detailed and sometimes mathematical representations of processes. In all cases, the models try to capture important characteristics of the process; this importance is however a relative concept, which depends on the purpose and audience of the models.

The usability, strengths and weaknesses of each model need to be identified and discussed with respect to the different perspectives of the design, and this requires

classifications of models. These are different approaches to classifying design models. In the following subsection, a series of classification frameworks are discussed, in an attempt to define those groups of models that are the foci of the literature review of this thesis.

2.4.1. Audience of Design Models

Models serve a 'user' for a specific purpose over a period of time (Eisenbart *et al.*, 2011). Design, as a process and as a product, includes a range of internal and external stakeholders; including designers, project managers, the directors of the companies for which the design team is considered a strategic business unit (SBU), and external stakeholders like shareholders and customers. To this list, we can add scientists and academic researchers.

Hazelrigg (1999) argues that while scientists focus on descriptive models, engineers and managers are more interested in predictive models. A review of the academic literature shows that while engineering researchers typically focus on developing tools and structures that support engineering design decisions, management researchers are more interested in project management and organizational issues involved in design and development (Smith and Morrow, 1999). O'Donovan *et al.*, (2003) present a table of the potential audience for a design process model, and their corresponding perspectives and interests (Table 2-3). This table can be used as a useful framework to understand different perspectives toward design process modelling.

Differentiation of models based on the audience of a model and their involvement and interest is a useful way of classifying models. The literature presents a few other classification frameworks, e.g., classification by purpose (Browning *et al.*, 2006; Wynn and Clarkson, 2018), by the degree of abstraction (Wynn and Clarkson, 2005), by coverage (stage vs activity) (Wynn and Clarkson, 2005), etc. In some cases, the classification scheme is extended beyond the boundary of 'process' models (e.g., Buede, 2000).

Such classification frameworks aim to facilitate understanding of the different approaches to design and development modelling, and hence, serve at least two purposes: first, provide a framework for selecting appropriate models for certain purposes (e.g., Browning, 2006) and second highlight the gaps in modelling approaches in order to guide future modelling developments (e.g. Wynn and Clarkson, 2005).

Participant	View of the design process	Involvement/interest/purpose
Engineer/designer	Detailed, limited scope	• Execution of design work
Operational Management	Wide scope, limited detail	• Optimisation of design process • Deployment of resources • Scheduling of tasks • Choice of design tools/methods • Risk management • Crisis response
Strategic Management	Multiple projects	• Evaluation/choice of potential projects • Process cost/timing • Investment in training / new tools
Academia	Dependent on research	• Forming/testing hypotheses • Communicating research to industry

Table 2-3 Audiences for design process modelling (O'Donovan et al., 2003)

2.4.2. Meta-Level Classification

Buede (2000) suggests that models can answer three types of questions: descriptive (or predictive), normative, and definitive.

- Descriptive models in science and engineering predict answers and explain processes, evaluating possible courses of action. Buede (2000) suggests they can be tested for predictive power.
- Normative models, also called prescriptive models, guide decision-making by addressing how an entity should behave. They are judged based on understandability and their ability to reflect decision-makers' intuition. However, Buede (2000) notes that in many cases, normative models cannot be tested due to the inability to examine the world under the same conditions.
- Definitive models aim to define entities and communicate interpretations of reality to a broader audience, requiring both rich languages and audience-friendly understandability.

Buede (2000) further provides a meta-level taxonomy of models by breaking models into physical, quantitative, qualitative and mental models. Table 2-4 provides his insight into this high-level taxonomy of models.

Model Categories	**Model subcategories**	**Involvement/interest/purpose**
Physical	Full-scale mock-up Subscale mock-up Breadboard	How much? How often? How good? Do they match?
Quantitative	Analytic Simulation Judgmental	How much? How often? How good?
Qualitative	Symbolic Textual Graphic	What needs to be done? How well? By what?
Mental	Explanation Prediction Estimation	All of the above!

Table 2-4 High-level taxonomy of models (Buede, 2000)

2.4.3. Functional Classification of Qualitative – Graphical Modelling Techniques

Another useful classification which is provided by Buede (2000) is classifying the graphical models based on their functional and operational approach into three categories: data modelling, process modelling and behaviour modelling.

Buede describes each category below and provides examples of modelling approaches in each category (Table 2-5).

- Data modelling: Tsichritzis and Lochovsky (1977) define a data model as "a set of guidelines for the representation of the logical organization of the data in a database... (consisting) of named logical units of data and the relationships between them (cited in Goodchild, 1992). In Buede's classification of models, data modelling addresses the relationships among the inputs and outputs of a system.

- Process modelling defines the functional decomposition of the system function and the flow of inputs and outputs for those functions. “Process models address how outputs are transformed from inputs via some function, activity, or task. … Process models can be used both at shallow and detailed levels of abstraction” (Buede, 2000)
- Behaviour modelling defines the control, activation and termination of system functions needed to meet the performance requirements of the system.

The following table provides examples of models in each category; the mentioned examples are mainly used in ‘systems and software engineering’.

Modelling Approaches	Modelling Methods
Data modelling	Entity-relationship diagrams (ERDs) Higraphs
Process modelling	Data flow diagrams (DFDs) IDEF0 N2 Charts
Behaviour modelling	Function Flow block diagrams (FFBDs) Behaviour diagrams (BDs) State-transition diagrams Statecharts Control flow diagrams (CFDs) Petri nets (PNs)

Table 2-5 Modelling approaches and methods (Buede, 2000)

2.4.4. Purpose-Based Classification of Activity Network Models

Browning and Ramasesh (2007) have published a comprehensive study of activity network-based process models of product development processes, identifying around 400 publications. They have used a classification framework based on the purposes of PD process models including project visualisation, project planning, project control, and project development. Project visualisation is related to documenting what, how, and when work should be done; project planning supports identifying appropriate ways of achieving the goals or objectives of the process through arranging the chosen activities in a network, defining the interdependencies between activities, positioning reviews and allocating resources; project execution and control are related to ongoing project management of a process by facilitating monitoring of the interim deliverables and determining corrective

action by comparing the current state of the project with the desired state; and project development supports other purposes from project development and infrastructure points of views like continuous improvement, organisational learning, training, and compliance (Browning and Ramasesh, 2007).

2.4.5. Resolution-Based Classification

One of the key differences among different design and development models is the degree of resolution in which the process is described. Wynn and Clarkson (2005) classify them into abstract, procedural, and analytical approaches. Abstract models offer high-level conceptual insights, lacking specific guidance. Procedural models detail practical aspects and concrete steps in the design process. Analytical models analyse and enhance specific design aspects. In a later study, Wynn and Clarkson (2017) add MS/OR as a fourth dimension, applying mathematical or computer analysis. They also introduce a scope dimension, ranging from individual mental activities to complex development programs involving numerous participants and suppliers (Wynn and Clarkson, 2018).

Table 2-6 shows a summary of the dimensions and categories of their proposed classification framework.

Dimension	Category	Models in this category
Scope	Micro-level	Focus on individual process steps and their immediate contexts.
	Meso-level	Focus on end-to-end flows of tasks as the design is progressed.
	Macro-level	Focus on project structures and/or the design process in context Type
Type	Procedural	Convey recommendations of best practice
	Analytical	Provide ways to model specific situations for analysis/improvement/support
	Abstract	Convey theories and conceptual insights into the DDP
	MS/OR	Develop insights by mathematical/computational analysis of representative cases

Table 2-6 The organising framework comprises two dimensions, each with several categories (Wynn and Clarkson, 2018)

2.4.6. Stage-Based Vs Activity-Based Models

Based on the work of Blessing (1996), which was founded on the earlier work of Asimov (1964), Wynn and Clarkson (2005) distinguished between stage-based and activity-based models. A stage is defined as a subdivision of the design process and may cover a considerable period of time. Generally, three stages can be identified in the majority of models: problem definition (setting the requirements), conceptual design and a detailed design (full product description); whereas an activity is a finer division than a stage and is related to the individual's problem-solving process. “A typical characteristic of an activity is that it reoccurs several times in any one process. Examples are: generating, evaluating and selecting” (Gericke and Blessing, 2011). Models can be purely stage-based; activity-based or a combination of both.

2.4.7. Graphic Techniques (Flow)

Several graphical models have been developed to represent the processes. From a sketching perspective, these models can be divided into the following categories:

- Linear process models: These models depict different design stages in a linear way assuming that each stage is done once, in a fixed order.
- Cyclic process model: These are generally abstract models with an emphasis on the iteration of activities.
- Spiralling process model: These are improved versions of cyclic models and reflect the evolution of ideas and as well as iterations of design activities.
- Non-cyclic iterative models: Huang and Gu (2006) identified three types of models in this category. These include sequential iteration models (Eppinger *et al.*, 1997), parallel iteration models (AitSahlia *et al.*, 1995), and overlapping models (Krishnan *et al.*, 1997).

2.4.8. Towards an Aggregated Classification Framework

The literature review shows a variety of approaches to the classification of models including design and development process models. The perspectives towards the classification of models are diverse and it is challenging to describe the relationship between them. Unifying

these viewpoints in a single framework can provide a multilateral view of a model and accordingly facilitate informed selection and use of models.

Figure 2.4 depicts the proposed aggregated framework comprising four main levels. The first three levels, adapted from Buede's classification frameworks, are mutually exclusive. Level 3 introduces a "product modelling" category. The fourth level represents dimensions rather than levels, with non-mutually exclusive categories resembling axes in a spider diagram. Models can adopt positions across all four categories based on purpose, coverage, degree of resolution, and employed graphical flow method. The subcategories of level 4 are mainly adapted from Wynn and Clarkson (2005), Browning and Ramasesh (2007), and Huang and Gu (2006), with an added "product life-cycle" subcategory under 'model coverage.' Note that Figure 2.4 only illustrates subcategories for qualitative, artistic, and mathematical graphics models. Other subcategories in the first two levels are outside the scope of this research and are not shown (Wynn and Clarkson, 2005; Browning and Ramasesh, 2007; Huang and Gu, 2006).

The aggregated framework is going to be used not only for analysing the various aspects of the reviewed models but also for justifying the focus of this thesis: i.e., qualitative process models. The next chapter provides a summary of some of the models in this class.

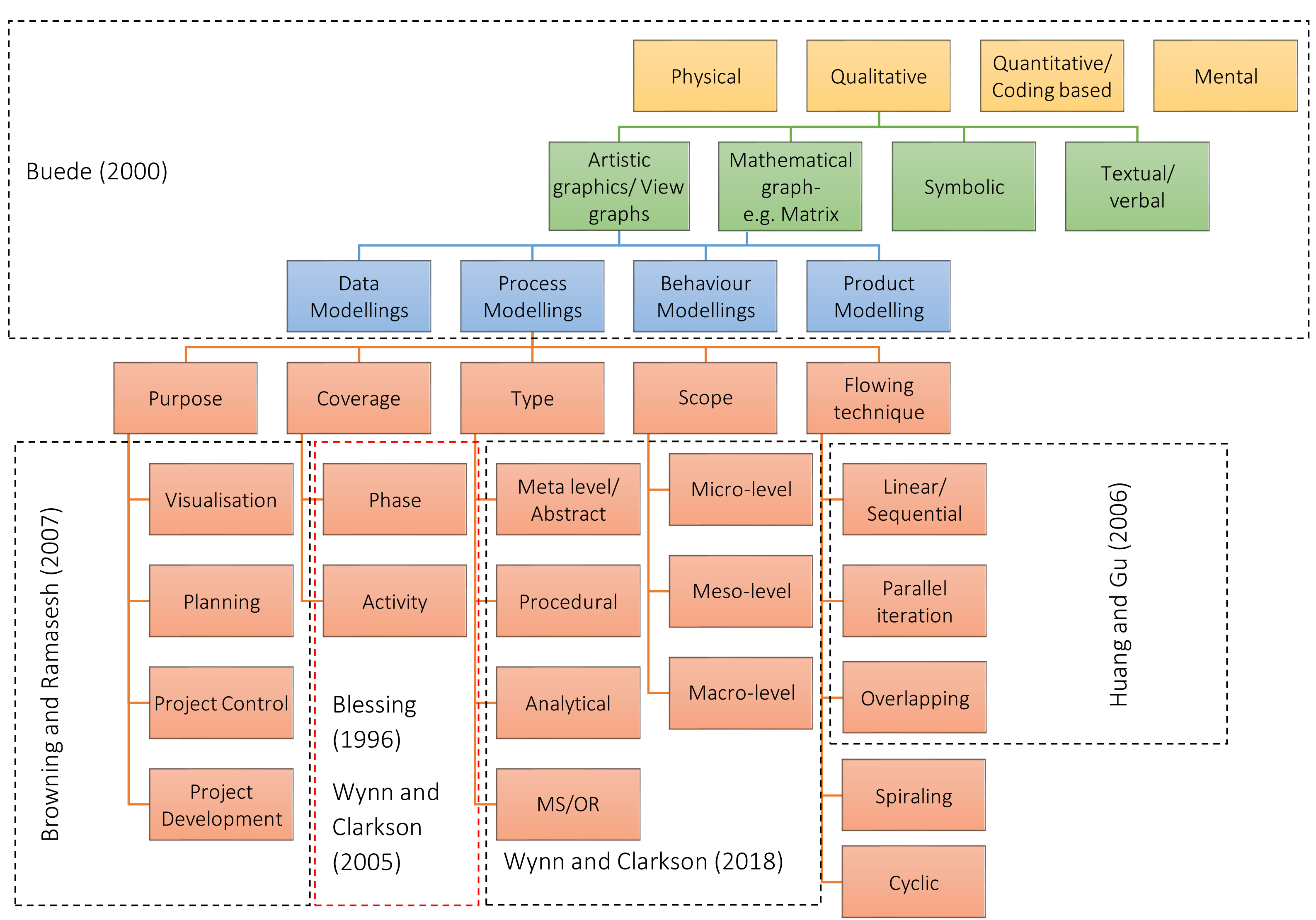

Figure 2-6 An aggregated representation of the different classifications of design process models

2.5. Graphical Models of Design Process

As discussed earlier, the starting point for this thesis is to establish an understanding of the design process and the range of activities undertaken by designers in order to find a design solution; A large variety of qualitative and graphical models are proposed in the literature to represent the design process. The most comprehensive study concerning reviewing process models of design and Product Development (PD) is a study by Browning and Ramasesh (2007). Using some filtering criteria, they identified 400 publications related to PD process modelling.

Providing such a comprehensive review of relevant publications is not practical within the scope of this research. Hence, decisions need to be made about what to include and what to exclude. The purpose of reviewing design models is to build an understanding of the design process, in particular from the search perspective. Hence, the models of interest to this thesis, are the ones which are descriptive and enable establishing an understanding of the design process and its life cycle. As discussed in the previous chapter, the models that fall within this category are qualitative and graphical process models. The models can be abstract, or procedural and more detailed. In any case, in shortlisting the models to be included in the following review, consideration was made to choose models with an emphasis on the explorative and problem-solving nature of the design process. Another factor that has been considered was the emphasis of the model on the problem definition stage of the design. Hence, the models which assumed the problem as defined and only focused on the actual 'manifestation of the design' were excluded from this review; as they were considered to have overlooked a fundamental element of design explorations, which occurs in the problem definition stage.

The chapter discusses major micro and mesoscale models, covering Procedural, Spiral, Divergence/Convergence, and 'V' models, reviewing multiple models within each category.

2.5.1. Pena And Parshall (1969) - Programming and Designing Model

This model comes from architecture, where programming refers to a phase of planning that precedes the design of a building. Pena and Parshall adapt the definition of programming from Webster that programming is "a process leading to the statement of an architectural problem and the requirements to be met in offering a solution." They further define programming as "problem-seeking" and design as "problem-solving." They also note,

"Programming is analysis. Design is synthesis." In their definition, design as problem-solving is a sequential process, where the problem needs to be defined before it can be solved.

Figure 2-7 shows the two-phase design process as proposed by Pena and Parshall (1969). In this image "schematic program and program development provide the information needed at the two successive design phases, going from the general scope to particular details. Programming is a two-phase process related to the two phases of design— schematic design and design development".

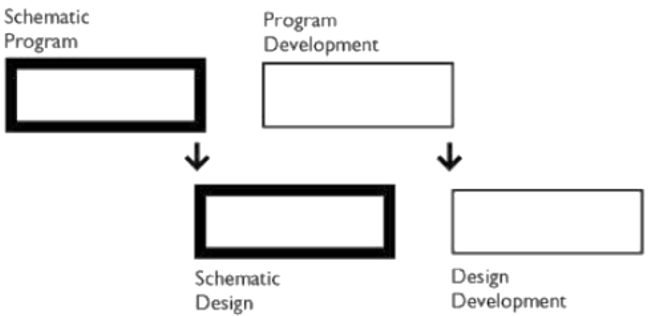

Figure 2-7 Two-phase design process (Pena and Parshall, 1969)

2.5.2. Cross (1994) - Four-Stage Model of The Design Process

Coming from an engineering perspective, Cross (1994) developed a four-stage model of the design process, based on the essential activities that the designer performs.

In this model, the designer first *explores* the ill-defined problem space and then *generates* a concept solution, which leads to the development of the design proposal. The proposal is subject to *evaluation* against the goals, constraints and criteria of the design brief. The end-point of the process is the communication of a design, ready for manufacture or integration into a more complex product (Cross, 1994). This model also includes a feedback loop between evaluation and generation steps.

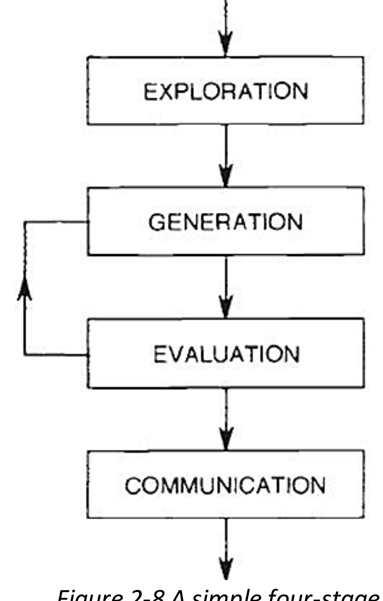

Figure 2-8 A simple four-stage model of the design process (cross, 1994)

Cross notes that the analysis of the problem is a small, but important part of the overall process. This model is categorised

as a problem-oriented model, which means that the designer is capable of formulating a solution-neutral problem statement (Wynn and Clarkson, 2005).

2.5.3. French (1999) - Block Diagram of Design Processes

In his book, Conceptual Design for Engineers, French (1999) proposed a stage-based model of design for engineering designers based on his observation from the industry (Figure 2-9). Circles indicate completed stages, while the rectangle signifies work in progress. French emphasizes that problem analysis is a crucial but relatively small part of the process. The output includes a statement of the design problem, limitations on the solution, and excellence criteria. The conceptual phase demands the most from designers, offering significant room for improvement. As schemes are detailed, a final choice is made, resulting in general arrangements. The detailing phase focuses on numerous crucial decisions. French's model incorporates feedback loops and acknowledges non-linear activity sequences, allowing for varying completeness across design aspects (Wynn and Clarkson, 2005)

Figure 2-9 Block diagram of design processes (French, 1999)

2.5.4. Markus (1969) And Maver (1970) - Map of The Design Process

Coming from architectural design backgrounds, Markus (1969b) and Maver (1970) argued that “a complete picture of the design method requires both a decision sequence and a design process or morphology” (cited in Lawson, 2005). The decision sequence in their models is cascaded to three layers of outline proposals, scheme design, and detail design. Each layer then consists of a four-stage process including the typical analysis-synthesis-evaluation process. Their model also shows the interdependence of stages, with the alteration from analysis and synthesis to appraisal and back again through the process (Figure 2-10).

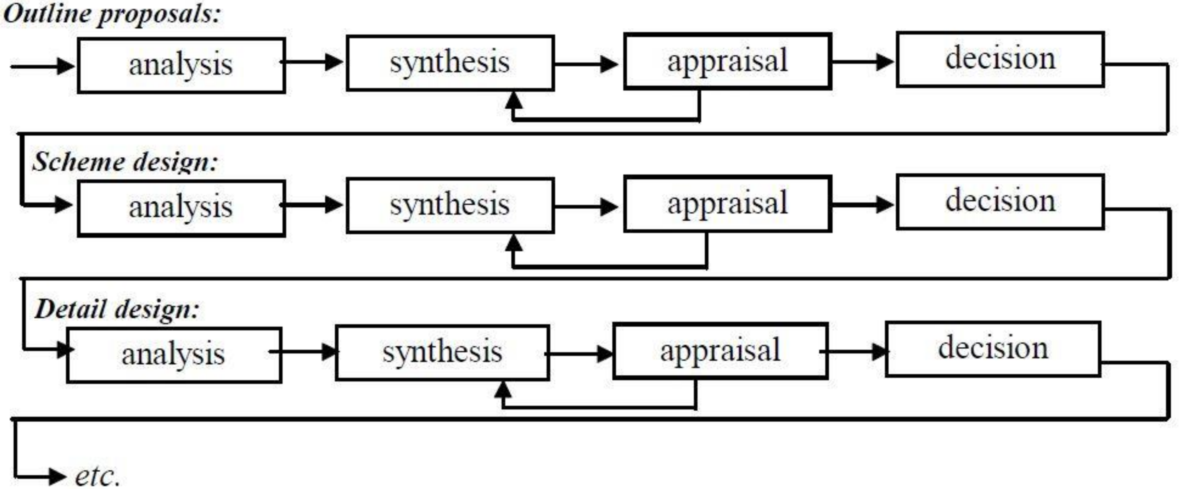

Figure 2-10 The Markus-Maver model of the design process (in Lawson, 2005)

2.5.5. Archer (1965) - Systematic Method for Designers

Bruce Archer, an industrial designer and mechanical engineer, proposed a significant design process model in "Systematic Method for Designers" (1965, 1984). His model includes inputs from designers' experiences, with the output as the communication of the design solution, featuring feedback loops. The design process involves six activity types across three phases: analytical, creative, and executive. Archer emphasizes the iterative nature of these stages, highlighting the critical "creative sandwich." He underscores the essential creative leap in designing and notes that automatic solutions indicate a non-design problem. Archer's model is depicted in Figure 2-11.

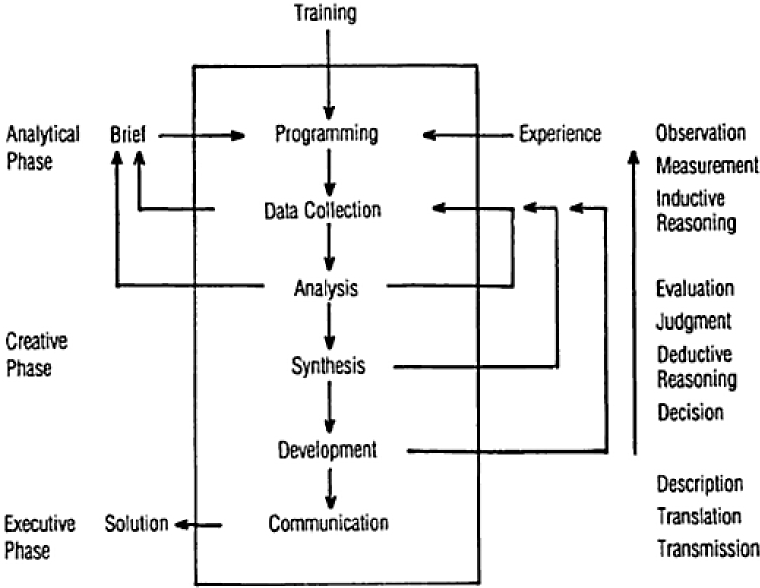

Figure 2-11 Systematic method for designers (Archer, 1965)

2.5.6. Cross (2000) - Systematic Problem-Solution Model of Design

In his book on engineering design methods, Cross (2000) introduces a seven-stage model that situates design within a problem/solution domain. His model integrates procedural and structural aspects, representing the sequence of methods and the commutative relationships between problem and solution, and hierarchical relationships between problem/sub-problems and sub-solutions/solution. Cross emphasises the co-evolution of design problems and solutions, highlighting the symmetrical and commutative nature of their relationships, as illustrated in Figure 2-12. He further adds that there is a constant transfer of the designer's attention backwards and forwards between the problem space and the solution space.

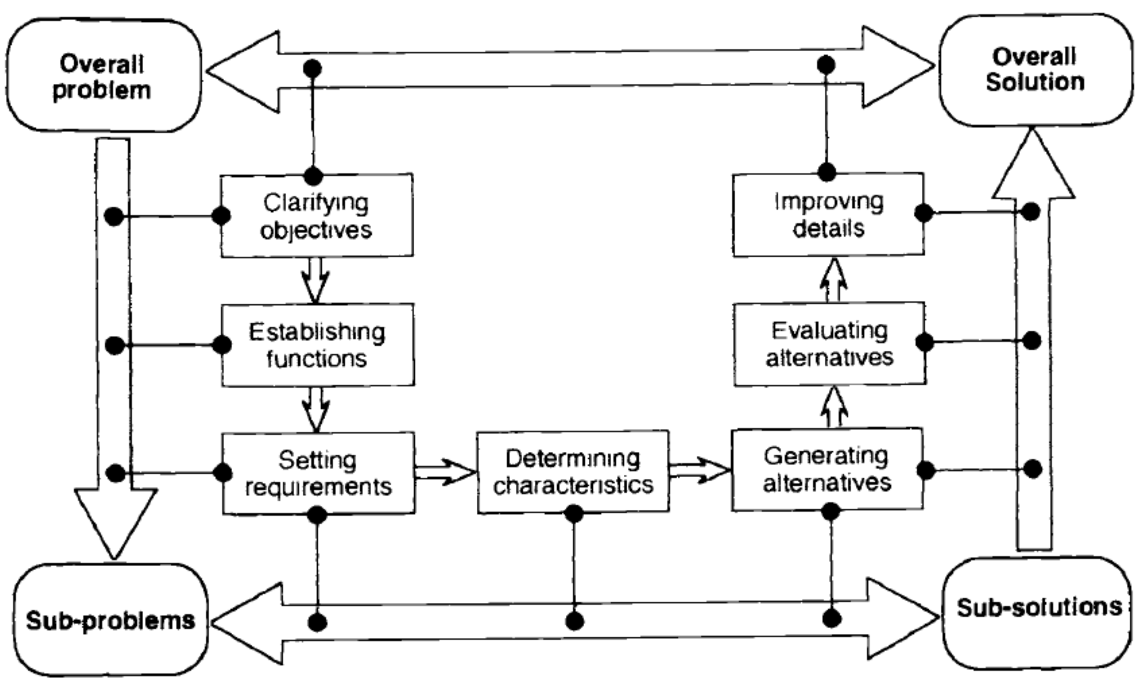

Figure 2-12 Seven stages of the design process positioned within the symmetrical problem (Cross, 2000)

2.5.7. Unger And Eppinger (2009) - The Traditional Staged Product Development Process

The most common Product Development Process is the traditional staged process shown in Figure 2-13, also known as the waterfall, stage gate, or phase gate model, which has been prevalent in US industry for decades (Cooper, 1990; Smith and Reinertsen, 1992; Ulrich and Eppinger, 2004). This model divides the process into sequential steps for linear product development progression, focusing primarily on the design stage. Despite the inclusion of iterations through reverse arrows indicating the potential to revisit earlier phases, feedback

is limited to specific checkpoints, making revisions challenging and costly (McConnell, 1996; Bassler *et al.*, 2011).

As suggested by Unger and Eppinger (2009) "Staged processes perform well in cases when products have stable product definitions and use well-understood technologies (as in the case of upgrades or maintenance improvements to existing product)". They are also suitable for projects "that are dominated by quality requirements rather than cost or schedule requirements. In these cases, where quality and error-avoidance are high priorities, the most attractive path is a direct one with early specification freeze and no subsequent changes that increase the likelihood of mistakes".

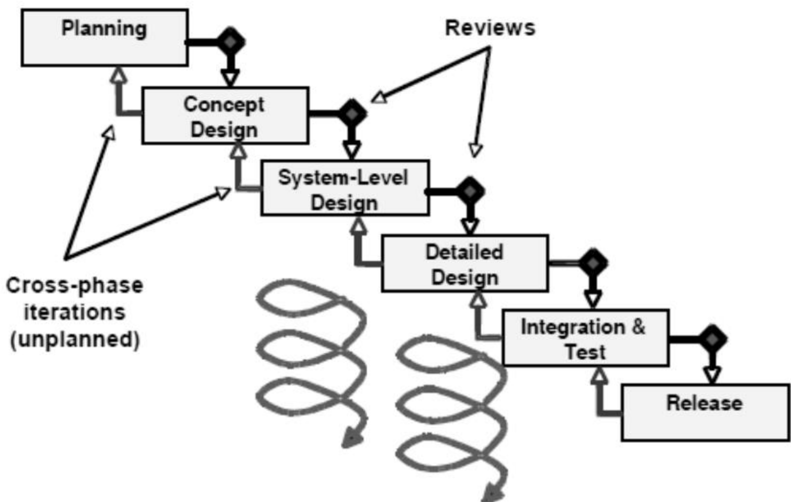

Figure 2-13 The traditional staged Product development process model (Unger and Eppinger, 2009)

2.5.8. Pahl And Beitz (1996) - Steps of The Planning and Design Process

Pahl and Beitz approach design from an engineering perspective, incorporating the psychological, systematic organisational aspects of design. Their model consists of four phases: planning and clarifying the task, conceptual design, embodiment design, and detail design, each with basic steps. After each phase, a decision-making step evaluates the outcomes to determine whether to proceed or revisit the phase, aiming for the smallest possible iteration loop (Pahl and Beitz, 2007). While they don't rule out iterations across phases, their method leans towards a "waterfall" approach, preferring iterations within phases (Tate and Nordlund 1996; Unger and Eppinger 2011, cited in Gero, 2017). They emphasize their methods foster creativity and necessitate objective result evaluation,

highlighting the critical transition from problem definition to solution concept by understanding the relationship between function and form.

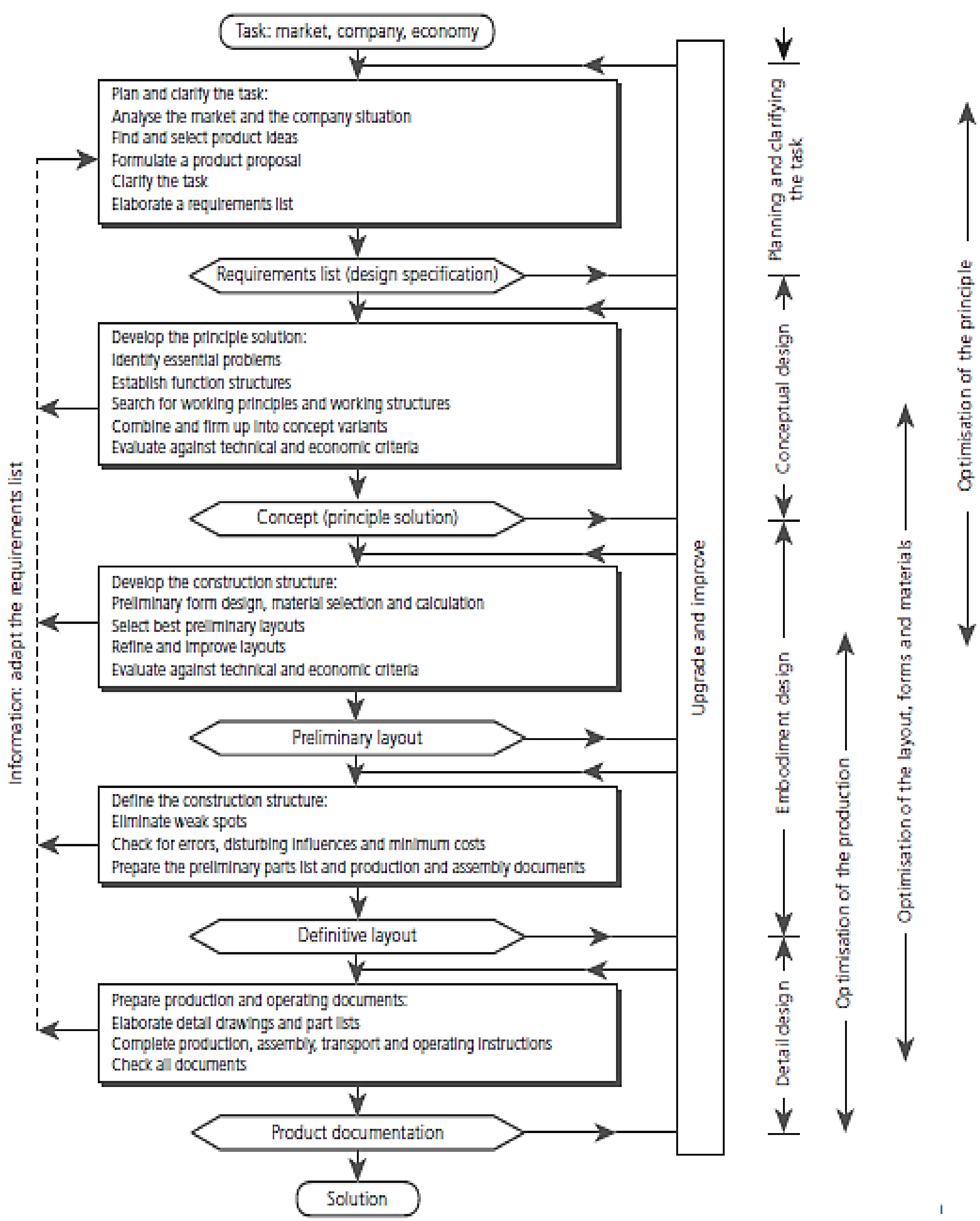

Figure 2-14 Steps of the planning and design process (Pahl and Beitz, 1996)

2.5.9. Banathy (1996) – Design Council (2005): Divergence and Convergence Model

Banathy presents a model from a system design perspective to demonstrate the evolutionary nature of design, identifying five territories: exploration/image creation, information and knowledge, solution space, experimentation/valuation, and modelling. His model (Figure 2-15) emphasises the iterative process of design, marked by cycles of divergence and

convergence across these spaces. Initially, the process involves diverging to explore various inquiry boundaries, design options, and core values. Following this, it converges to select a promising future system image. This divergence-convergence pattern is crucial throughout the design phases, including the definition, specifications, functions, enabling systems, and systemic environment. Banathy (1996) highlights the importance of this iterative approach in fostering creativity and narrowing down to the most desirable solution, ultimately guiding the design towards development and delivery.

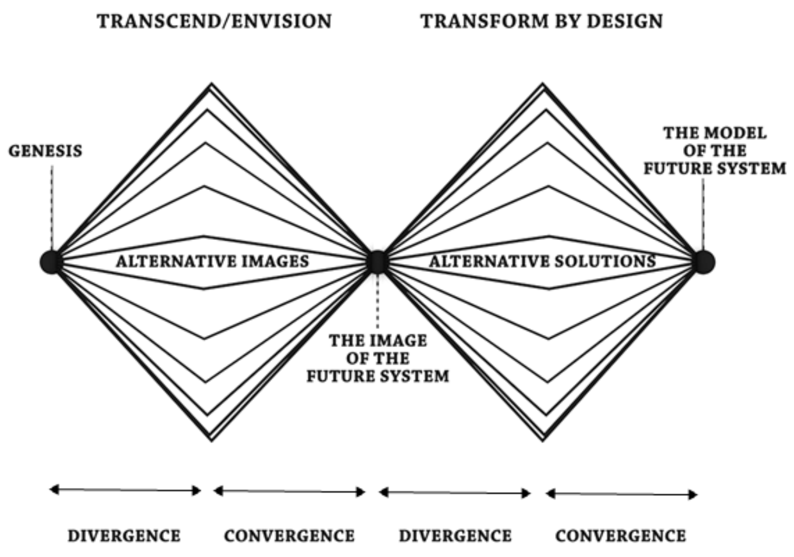

Figure 2-15 The dynamic of divergence and convergence (Banathy, 1996)

Another famous model which relates to Banathy's model is the design council's double diamond model (Design Council, 2005). The model, depicted in Figure 2-16, divides the design process into four distinct phases – Discover, Define, Develop and Deliver.

Discovery marks the project's beginning, focusing on gathering initial ideas and understanding user needs through market and user research. Following this, the Define stage organizes these findings into a clear brief, outlining the core design challenge and employing project development and management. The Development phase then explores solutions through prototyping, testing, and iteration, emphasising refinement and multi-disciplinary collaboration. Finally, the Deliver stage finalizes and launches the product, incorporating final testing, approval, and feedback mechanisms.

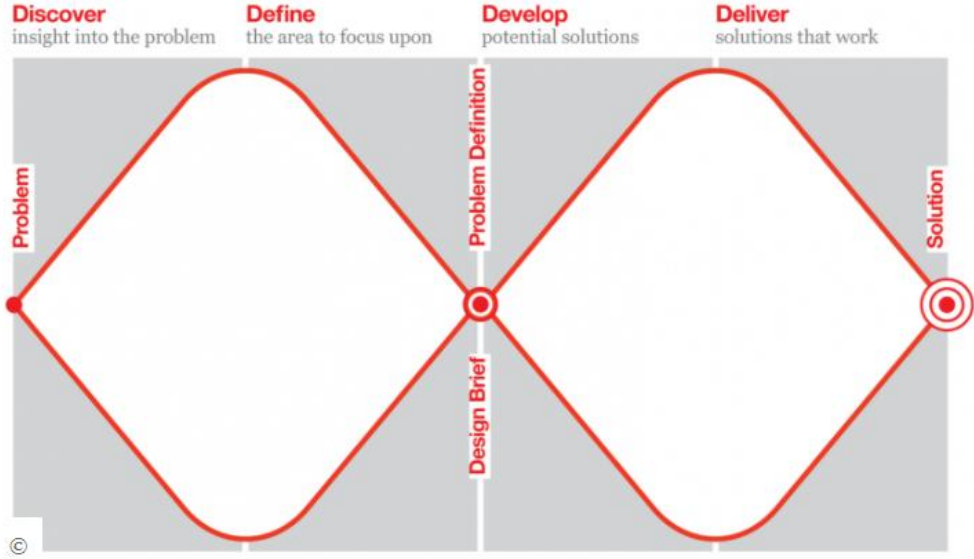

Figure 2-16 The 'Double Diamond' design process model (Design Council UK, 2005)

Banathy's and the Design Council's Double-diamond models emphasise alternating between divergence (expanding and exploring ideas) and convergence (focusing on practical solutions). The process begins with broad idea collection, shifts to narrowing down based on the design's purpose, and repeats this cycle to explore alternatives before settling on a final solution. This method, which structures the design process into clear steps and prioritises exploration, is crucial for understanding design from a search perspective, highlighting its significance to the thesis objectives.

2.5.10. Forsberg And Mooz (1998) - 'V' Model

Another popular macro model of design is the V-model, which is known to be a modified version of the Waterfall model (Tolba and Mushtaha, 2008). The 'V' model is requirement-driven (Forsberg and Mooz, 1998), in the sense that the requirements are considered as 'controls' throughout the different stages of a project lifecycle. While the waterfall model mainly stresses the flow down of requirements as the design details evolve, the V model adds an emphasis on testing and verification of the output of each stage.

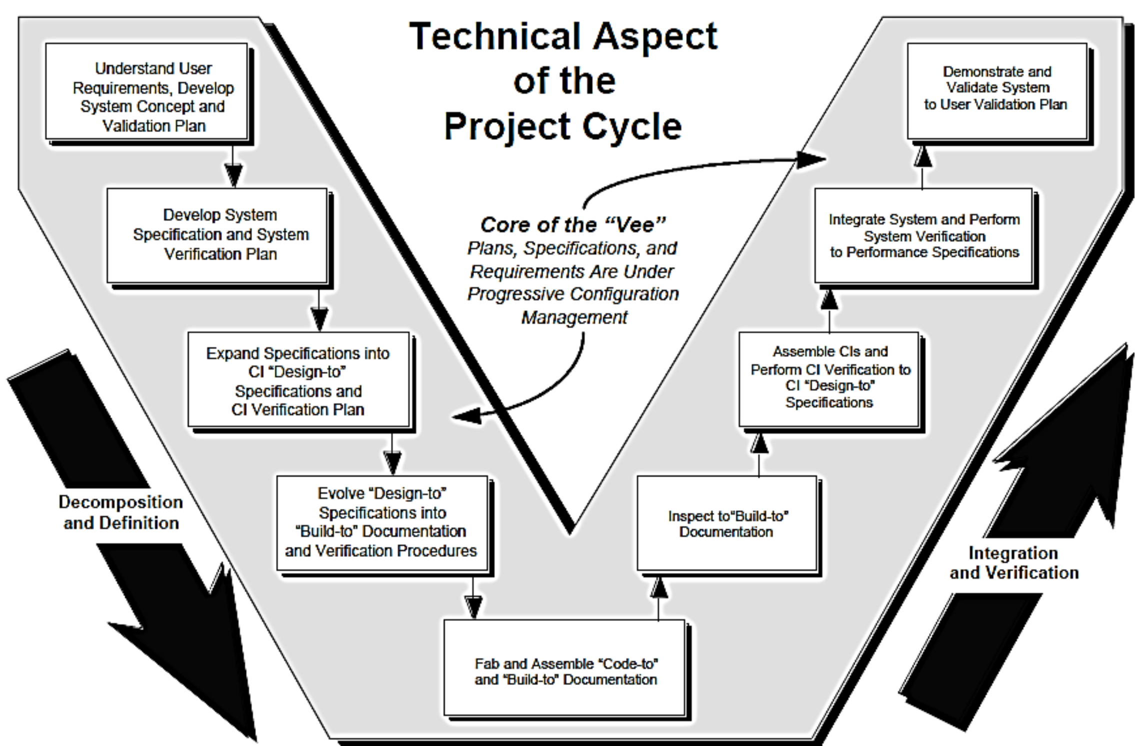

Figure 2-17 The "V" Model: the technical aspect of the project cycle, (Forsberg and Mooz, 1998)

In the V model, both the design problem and verification requirements are outlined early, with components integrated later (Browning and Ramasesh, 2007). This approach ensures that development stages, verification criteria, and testing scenarios are established upfront. Forsberg and Mooz (2005) describe the V model as effectively representing system evolution through its focus on decomposition and integration. The model illustrates a cycle with development activities on one side and integration/verification on the other, emphasizing a direct link between design and verification. It operates on a stage-gate principle, requiring each phase's output to be approved before proceeding, thus sharing some limitations with gate models, such as predefined stages and verification criteria that may restrict flexibility in managing risks and uncertainties. Various versions of the V model exist, each with its own terminology and representations.

The Dual Vee Model (Figure 2-18), which is used in System Engineering (SE), addresses the complexity of merging system architecture and entity development at each level of decomposition. It features Entity Vees orthogonal to the Architecture Vee, showcasing concurrent development (Forsberg and Mooz, 2005). The ability to develop 'entity Vees' in the this model provides it with an analytical functionality and therefore the model can be classified as a procedural and analytical approach. The idea of 'entity Vees' can be applied to

each level of decomposition and as a result, provides more detailed information about the activities within each step. Therefore, the V model can be classified both as a stage-based and activity-based model. Like stage-based models, the V-model not only supports project planning but also serves project control through an emphasis on evaluation.

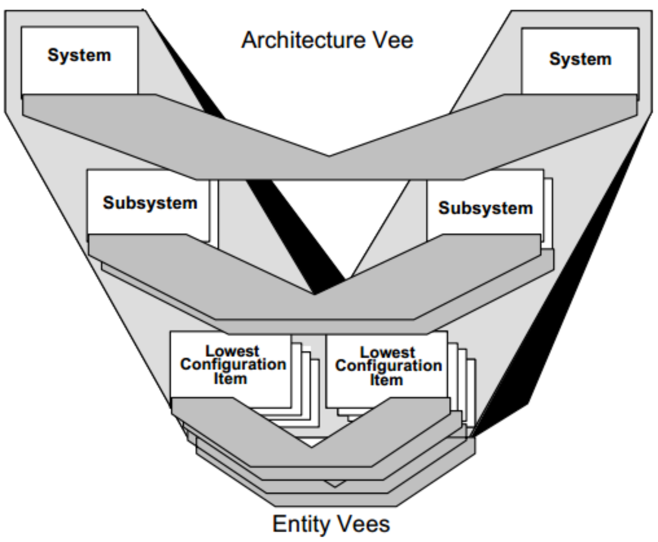

Figure 2-18 Architecture and entity Vees intersecting (Forsberg and Mooz, 2005)

2.5.11. Evans (1959), Andrew (1981) and Boehm (1988 & 1994) – Spiral Development

Evans first introduced the concept of the design spiral in 1959 for visualising and modelling the process of ship design (Figure 2-19). He illustrated the design process as a spiral with progressive iterations, from requirements to full definition of specifications. The model highlights that many design parameters interact in a sequential process, with increasing details, until a single design which fulfils all constraints is reached. The interaction implies the need to find trade-offs between interdependent factors. As the project progresses and at each iteration, the interdependencies are gradually resolved, until a balanced solution is accomplished. A major feature of this model is that design is a sequential (rather than concurrent), converging and iterative process.

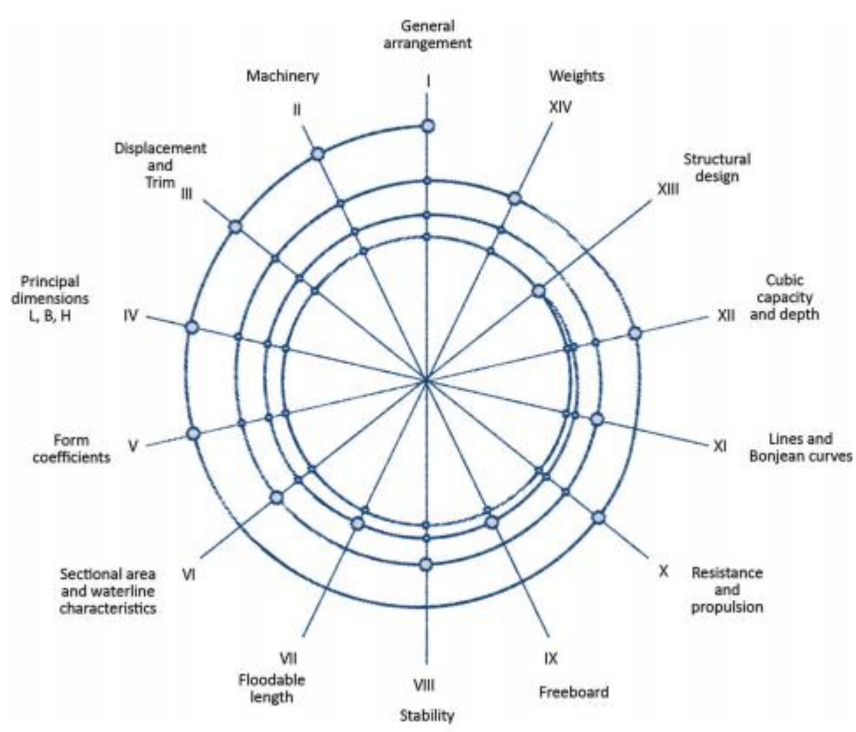

Figure 2-19 Evan's general design diagram (1957)

The model has been developed further to incorporate more features of the design process and employed in other design fields. Buxton (1972) added economic issues into the spiral and Andrews (1981) introduced time as a third dimension to the model (Figure 2-20). He stated that with this three-dimensional representation "many dialogues and constraints on a designer can be shown as fundamental to the process" (cited in Mistree, *et al.*, 1990).

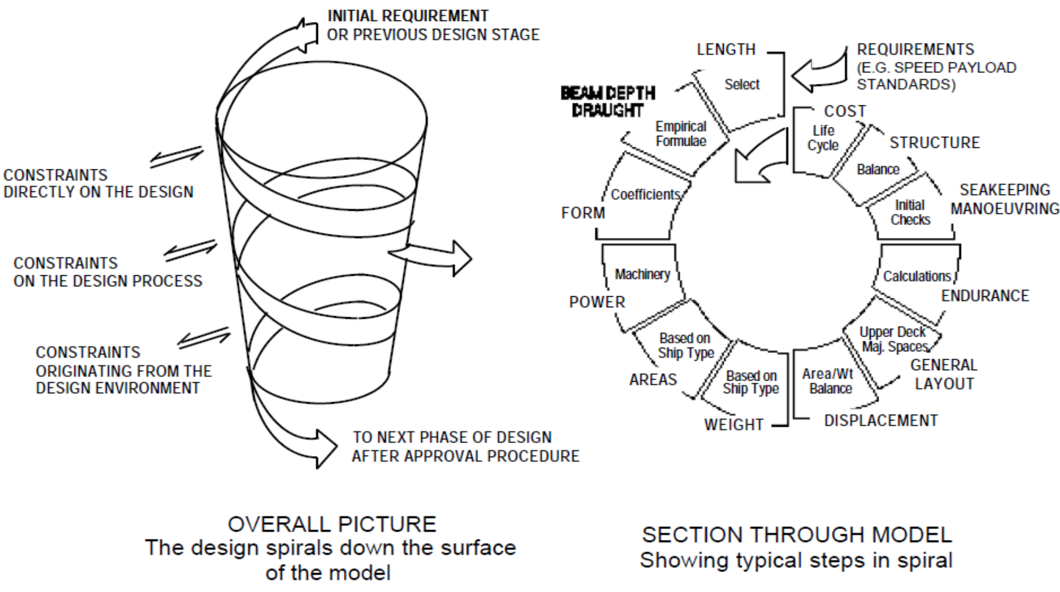

Figure 2-20 Overall model of the ship design process (Andrews, 1981, cited in Mistree, et al., 1990)

The spiral drawn by Evans illustrates convergence towards a product; however, there is a divergent aspect associated with increasing information. This was first highlighted by Buxton (1972). In 1988, Boehm presented the idea of using the spiral model in the software design process with the spiral direction reversed reflecting increasing details and completeness of the information (Figure 2-21). This new version of the spiral model is complementary to that originally proposed by Evans which considers convergent refinement of a set of design parameters.

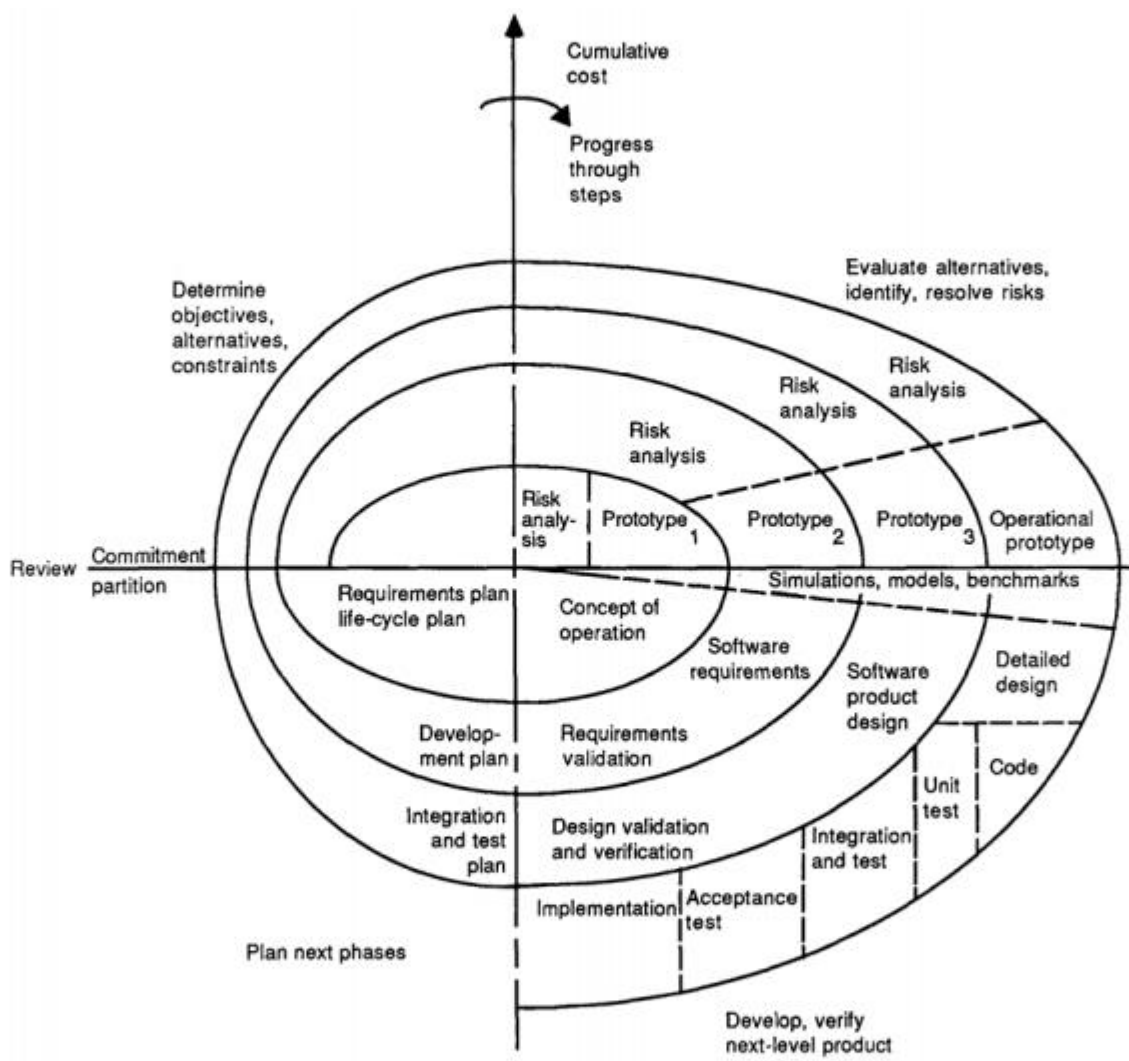

Figure 2-21 Spiral development (Bohem, 1988)

"Cyclic concurrent engineering; risk driven determination of process and product; growing a system via risk-driven experimentation and elaboration and lowering development cost by early elimination of nonviable alternatives and rework avoidance" are features of spiral models which according to Boehm (2000) reflected in his model of spiral product

development. He further argues that the spiral model is actually a risk driven process model "in which different risk patterns can lead to choosing incremental, waterfall, evolutionary prototyping, or other subsets of the process elements in the spiral model diagram" (Boehm, 2000).

Many other scholars have tried to advance the model further. In an attempt to overcome some of the limitations of the model in terms of difficulties in determining objectives, constraints and alternatives at the beginning of each cycle, Boehm (1994) himself has introduced the Win-Win spiral model (Figure 2-22). The Win-Win Spiral Model uses the Theory W (win-win) approach (Boehm, 1991) to converge on a system's next-level objectives, constraints, and alternatives.

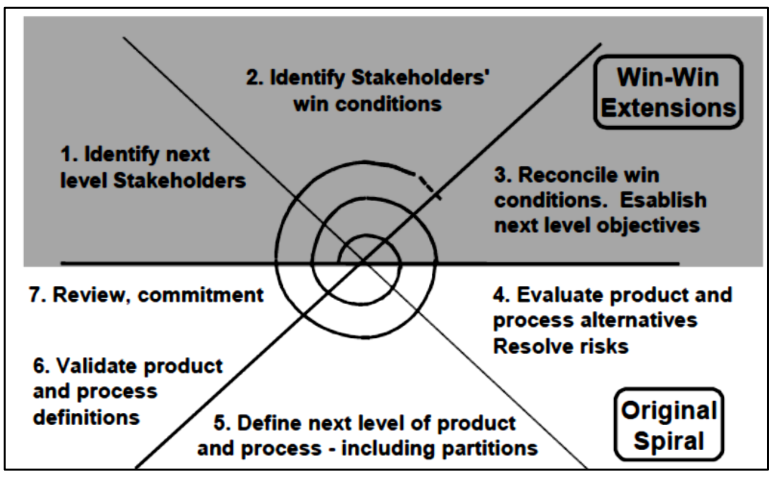

Figure 2-22 The Win-Win spiral model (Boehm, 1994)

This approach "involves identifying the system's stakeholders and their win conditions and using negotiation processes to determine a mutually satisfactory set of objectives, constraints, and alternatives" (cited in Boehm, 2000).

Muench *et al.* (1994) propose a model for the software engineering process, akin to Boehm's, but with a greater focus on evaluation and feedback (Figure 2-23). These enhancements to the spiral model accommodate features like evolution, risk, feedback, and iteration. A notable limitation, however, is its treatment of the design process as sequential rather than concurrent, overlooking the possibility of overlapping activities. Despite Boehm's assertions, this limitation suggests a lack of concurrency in the design spiral's execution. Importantly, the win-win spiral model introduces the capacity to represent stakeholders'

viewpoints, offering a way to incorporate aspects of design, such as strategic alignment or social collaboration, that other models might not effectively capture.

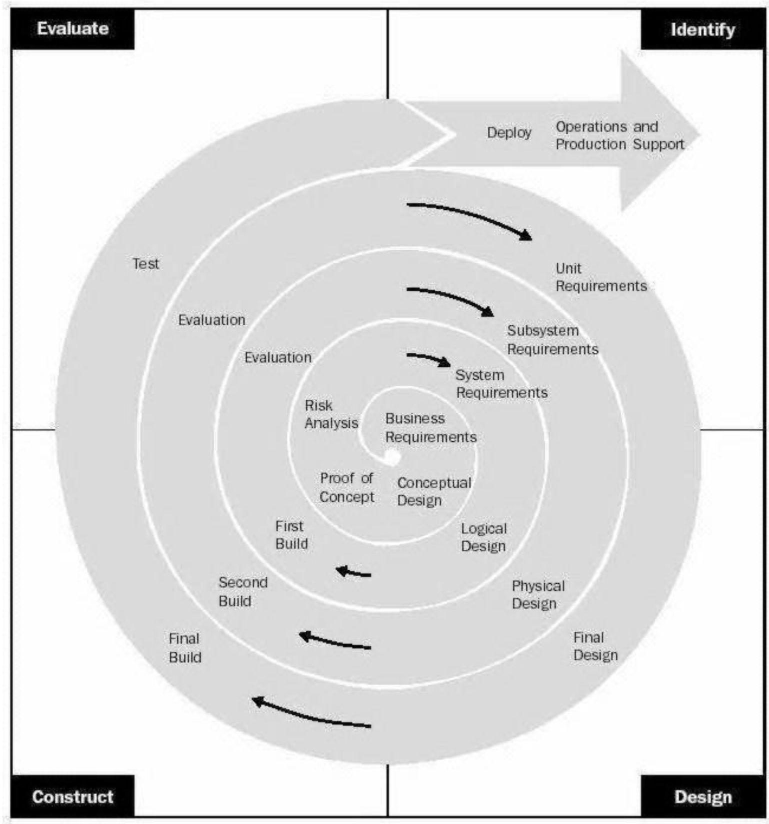

Figure 2-23 Representative (iterative) software development model (Muench, 1994)

The spiral model, beyond being a broad macro model of design, offers detailed functionalities, allowing it to depict specific design process aspects and adapt to various industry needs. It's both a procedural method and an abstract-level tool, encompassing the design process's entire lifecycle through four stages: identify, design, construct, and evaluate (Figure 2-23). It structures the Product Development (PD) process, aiding in project planning. Initially a descriptive model showing design practices, it's now widely accepted as a prescriptive framework guiding enterprises in their design methodologies (Mistree *et al.*, 1990; Browning *et al.*, 2006). Recognised for its significant influence and comprehensiveness, the spiral model continues to offer potential for further refinement, as noted by Brookes (2010).

2.5.12. Ulrich (2011) - Four Information Processing Steps

Ulrich presents a model of the design based on the information processing view of design, largely consistent with what was articulated by Herbert Simon in the 1960s (and 1996), in his book 'the science of the artificial. "From this perspective, design is part of a human problem-solving activity beginning with a perception of a gap in a user experience, leading to a plan for a new artefact, and resulting in the production of that artefact. This problem-solving process includes both design and production of the artefact (Ulrich, 2011). Design transforms the gap into a plan (e.g., in the format of drawings, computer models or parameter values) and production transforms the plan into an artefact.

The design portion of Ulrich's model is decomposed into four steps: 1) Sensing the gap in user experience; 2) Defining the problem, which is an explanation of why the gap is being experienced by the user 3) Exploring alternatives and 4) selecting the plan (Figure 2-25).

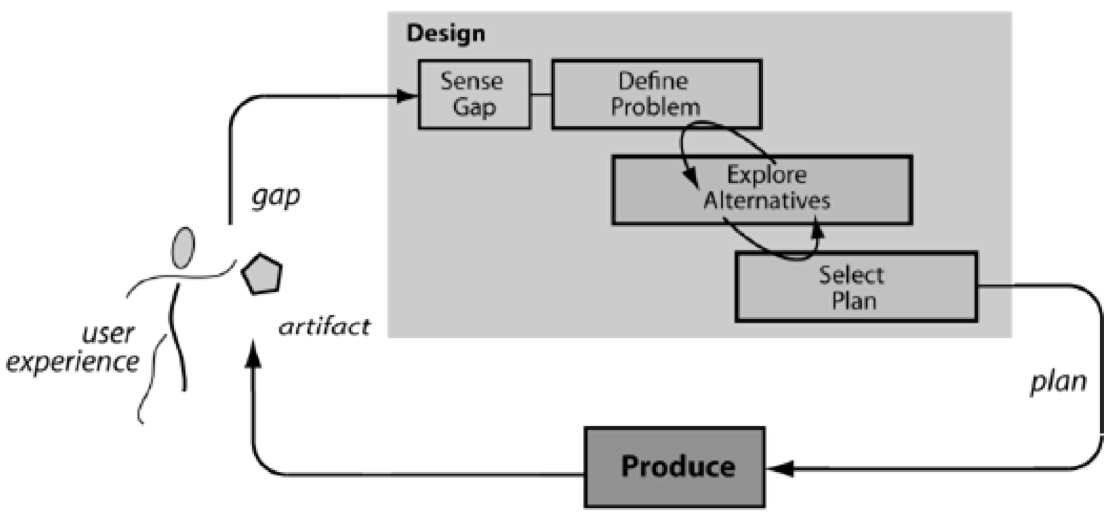

Figure 2-24 Design as four information processing steps (adapted from Ulrich, 2011)

The first step relates to the identification of user needs that are not being fulfilled in the current state and /or the recognition of conditions for having a solution with improved quality. This step is generally an obvious element of professional design processes, which is articulated in the form of a design brief, customer needs list or such documents.

The exploration stage typically includes exposing more than one solution, and hence design requires some sort of evaluation and selection from among alternatives. Ulrich notes that some designers consider numerous alternatives simultaneously when selecting a plan,

while others articulate, evaluate, and refine plans iteratively and select the first plan that is good enough.

Though an abstract model, Ulrich's model reflects the exploring nature of the design and approaching the design as a problem-solving process, and in that perspective, it is a very useful descriptive model of the design process.

2.5.13. Reviewing Models- Remarks

As discussed, numerous models focus on many interesting and important aspects of the design process, including problem identification and analysis, iteration, concurrency, decomposition, synthesis, evaluation and detailed design. What was reviewed in this section covers only a very small portion of the spectrum, which as mentioned earlier includes models that were selected based on their relevance to the scope and objectives of this thesis.

Table 2-7 provides a comparison of the reviewed models, based on the characteristics of the design process, as discussed in section 2.2. That table also provides a short description of the essence of each model.

Model name	Graphics	The essence of the model	Intuitive/ creative	Iterative	Concurrent	Co-Evolutionary	Risky	Collaborative/ Social	Complex and Hierarchical
Programming and designing model		Two-phase design process including “problem seeking” and “problem-solving.”	Not covered	Not covered	Not covered	Not covered	Not covered	Not covered	Not covered
Four-stage model of the design process		The stages are Exploration, Generation, Evaluation and Communication	Not covered	Limited iteration, between solution generation and evaluation stage	Not covered	Not covered	Not covered	Not covered	Not covered
Map of the design process		Include a decision sequence and a design process	Not covered	In each design phase between synthesis and appraisal	Not covered	Not covered	Not covered	Not covered	The decision is cascaded to three layers; also, synthesis in each layer
Systematic Meth od for Designers		The model identifies six types of activities summarised into three broad phases of analytical, creative and executive.	The creative phase requires involvement, subjective judgement, and deductive reasoning; also training and expertise are considered as inputs as well as the brief	"Stages are overlapping ... with frequent returns to early stages”.	Overlapping stage	Data collection loops	Not covered	Not covered	Embedded in the data analysis and synthesis stages
Systematic probl em-solution model of design		A seven stages model of the design positioning the design into a problem/solution domain.	Not covered	a constant transfer of the designer's attention backwards and forwards between the problem space and the solution space.	Generating Alternative solutions	symmetrical & commutative relationship between problem and solution, and between sub-problems and sub-solutions	Not covered	Not covered	Arrows showing the hierarchical relationships between problem/sub-problems and between sub-solutions/ solution
Block diagram of design processes		A stage-based model showing stages reached and works in progress.	Not covered	accounts for the feedback loop and iteration between different steps	Conceptual design leading to selected themes	Not covered	Not covered	Not covered	Not covered

Model name	Graphics	The essence of the model	Intuitive/ creative	Iterative	Concurrent	Co-Evolutionary	Risky	Collaborative/ Social	Complex and Hierarchical
Waterfall model		A stage-based process including review gates at the end of each phase.	Not covered	Most iterations occur within stages; Cross-phase iteration exists; however, the model only provides feedback loops at the gates	Overlapping stages	Not covered	Not covered	Not covered	System-level design
Steps of the planning and design process		Comprises the four phases of planning and clarifying the task, conceptual design, embodiment design and detail design. Each phase then includes a set of basic steps.	the creative leap between problem definition and solution concept	Each phase comprises a sequence of activities that may be executed iteratively. After every phase, a “decision-making step” is performed which may lead to reiterating the phase	Several preliminary layouts might develop to a certain degree	Not covered	Not covered	Not covered	Establishing function and construction structure
Divergence and Convergence model (Double Diamond)		four distinct phases – Discover, Define, Develop and Deliver	Not covered	Iteration is reflected in Banathy’s model as repeating the process of divergence and convergence	Options are considered in the discovery stage, and alternatives are created in the development stage	Not covered	Not covered	Not covered	
V model		The ‘design problem’ and the ‘verification requirements’ are decomposed in the early stages of the development process. The developed components are then integrated into the later stage	Not covered	Not explicit in the model, within-stage iteration is possible but not after progressing to the next stage	Dual Vee- the system solution at each level of architecture	Not covered	Not covered	Not covered	system decomposition and integration activities are one of the key aspects of the model
Spiral development		Design parameters interact in a sequential process, with increasing details, until a single design which fulfils all constraints is reached	Not covered	The design process is considered as a spiral with progressive iterations	Cyclic concurrent engineering	the interdependencies are gradually resolved until a balanced solution is accomplished	Emphasis on risk analysis and reduction throughout the cycle	Not covered	Embedded in the integration test stage.
Information processing Model		design is part of a human problem-solving activity decomposed into four steps: 1) Sensing the gap in user experience; 2) Defining the problem, 3) Exploring alternatives and 4) selection of the plan	human problem-solving activity	inter and intra-stage iteration, between defining the problem and exploring alternatives	Exploring alternatives, and hence design requires some sort of evaluation and selection from among alternatives	Overlap and feedback loops between defining a problem and exploring alternative stages	Not covered	Not covered	Not covered

Table 2-7 A comparison of reviewed models

The table shows that each model has its own strengths in terms of highlighting certain aspects of the design process. Despite the divergence of the models, many of them have common features like recognising the iterative nature of the design. This is of no surprise; iteration is such a fundamental and obvious part of the design process, which is almost unmissable from any perspective of the design process. Osborne (1993) found that iteration accounted for between one-third and two-thirds of the total development time for projects at a major manufacturing firm. He also found that unpredictable iteration is the main cause of variability in the lead times of projects (Osborne, 1993, cited in Eppinger et al, 1997). Some less obvious characteristics of the design, however, are highlighted in very few models. For example, the role of human intuition in the design process is only reflected in two of the models: Archer's (1965) Systematic Method for Designers and Ulrich's (2011) information processing model. The same is true about the spiral model of design, which seems to be the only high-level model that emphasises continuous risk evaluation throughout a process. However, in some cases the enhancements to a model have significantly improved its analytical power, for example, the idea of Dual Vee, has enabled the 'V' model to capture elements of concurrency of the design process. The table could guide how models can be improved by getting ideas from other models. For example, consideration of the designer's experience as an input to the process can easily add an intuitive angle to many of the models.

The analysis also shows the complexity of modelling requirements for the design process and the inability of existing models to adequately represent the characteristics of the design process and accordingly provide designers and managers with appropriate tools to support decision-making. The discussion also showed that ideas from one modelling approach could be applied to another model to extend its capabilities and coverage. This can provide scope for introducing new models or extending the existing models so that they more properly and adequately represent development and design processes as well as their specific features and modelling requirements. The evolution model presented earlier in this chapter can be considered as a preliminary attempt to take ideas from stage-based models, the V model, spiral development, and represent them in a single conceptual model.

The review of the models also shows that while the complexity of the solution development stage is represented in many of the models, not many models lay emphasis on the complexities of the problem definition stage and the exploration needed for this purpose;

in fact, although in a few of the models the problem definition stage was illustrated with some details (e.g. Pahl and Beitz, 1996; Cross, 2000) the majority of the models only briefly refer to this stage (e.g. Boehm, 1988; Muench, 1994 & Unger and Eppinger, 2009).

The diversity of models not only suggests design is a multi-perspective and multidisciplinary process but also shows that design is a multi-phased process. The design performance hence can be expected to be affected by the interaction between these phases, including problem definition and solution development stages.

2.6. Theories of Design

This section provides a review of some of the well-recognised theories of design. As discussed in section 2.3, this thesis distinguishes between models and theories of design.

In science, 'theory' often explains empirical observations and lays the foundation for generating testable hypotheses (Campbell *et al.*, 2014). Popper (2002) sees a scientific theory as experimentally falsifiable, while Gorelick (2011) views it as a discipline for forming hypotheses. Given these views and the characteristics of models and theories in Table 2-2, the following theories are reviewed: Herbert Simon's Sciences of the Artificial (Simon 1996), Design as a Reflexive Practice (Schön, 1983), Design as Building and Reusing Artefact (Reddy *et al.*, 1998), General Design Theory (Yoshikawa 1981, Tomiyama *et al.* 1987), Concept-Knowledge theory (Hatchuel *et al.* 2009), and Decision-Based Design (Hazelrigg,1998; Marston *et al.*, 1997; Krishnamurty, 2006; Lewis *et al.* 2006b).

It's important to note that while there are many models of the design process, actual theories of design are few. Consequently, significant works like Axiomatic Design (Suh, 2001) and the TRIZ methodology (Altshuller, 1994), which propose design methods or models rather than theories, are not included in this review. Similarly, works often referred to as design theories, like the systematic design method of Pahl and Beitz (Pahl *et al.* 1996), or Archer's (1965) Systematic Method for Designers, were discussed earlier under design models.

2.6.1. Sciences of The Artificial

Herbert Simon's work, "The Sciences of the Artificial" (Simon, 1988, 1996), though not strictly a design theory, underscored the importance of a scientific approach in design, distinguishing design from natural sciences, social sciences, and humanities by its focus on creation. Simon

advocated for design as a logical search process accessible to anyone aiming to transform existing situations into preferred ones, proposing the General Problem Solver (GPS) as an ideal tool for navigating from current to desired states through selective action sequences.

Simon also outlined a design curriculum that integrated utility and statistical decision theories, optimization techniques, formal logic, heuristic search, resource allocation, and complex structure organisation to foster a scientific theory of design. He introduced 'bounded rationality' and 'satisficing' to acknowledge human limitations in processing complex information, suggesting that designers often settle for good enough solutions rather than optimal ones due to these cognitive constraints.

Despite its influence, Simon’s model has faced criticism for overly quantifying the design process and underestimating the complexity and ill-structured nature of many design problems. Critics argue it overlooks the inherently social, political, and cultural aspects of design. Subsequent scholars have built on Simon's ideas, exploring them within AI and extending them to accommodate greater social interaction and recognize design's social dimensions. Despite criticisms, Simon’s framework remains a pivotal reference in design and related fields, highlighting the enduring relevance of his concepts in shaping design research and practice.

2.6.2. Design as a Reflexive Practice, Schön (1983)

In "The Reflective Practitioner," Schön (1983) explores the concept of reflective practice in design, emphasizing the tacit knowledge that practitioners possess, often more than they can articulate. He introduces key notions:

- Reflection in action: Reflecting on one’s behaviour as it occurs, to optimize subsequent actions, responding to surprises with improvisation.
- Knowing in action: The tacit knowledge underlying the ability to act competently.
- Reflection on action: Reflecting after the event to enhance future practice.
- Ladders of reflections: A recursive process, where action and reflection lead to further reflection.

Schön (1983) prompts a re-evaluation of the balance between technical expertise and creative intuition in advancing professional skill, setting his perspective apart from Simon’s

analytical approach to design as a series of logical problems to be solved. He advocates for a practice-centred understanding of design, suggesting that the essence of design lies in the cyclical dialogue between making and reflecting on what is made, a process fundamental to the work of architects and psychoanalysts alike. This reflection is not an adjunct to practice but its very heart, according to Schön (Sköldberg *et al.*, 2013). He challenges the conventional view of design as mere problem-solving or data processing, critiquing the assumption that design problems are simply there to be found. Instead, Schön posits ‘problem setting’ as a dynamic process whereby designers actively construct problems within the context of uncertain and complex situations through a process of identification, exploration, and iterative refinement.

Schön advocates a design approach that diverges from the conventional notion of a 'search within a problem space.' He envisions designers as creators of their design world, setting the parameters of their problem space and crafting strategies to navigate it. Through reflective dialogue with the design context, designers continuously 'frame' and 'reframe' challenges, leading to new insights that fuel further reflection and action. This iterative cycle of action, reflection, and adaptation allows designers to engage deeply with complex situations, making sense of them through the process of attempting change. As designers act, their interventions often lead to unexpected outcomes, enriching the design context with new meanings. This dynamic interaction, where the design context 'speaks back' and the designer listens and adjusts, is central to Schön's conceptualization of the design process, emphasizing a fluid, ever-evolving understanding of both problems and solutions.

Schön, building on Simon’s insights, explores the idea that designers often don't foresee all outcomes of their actions due to inherent limitations in human cognition. He and Wiggins (1992) point out that it's impossible for individuals to predict every consequence or quality of their actions before they happen, yet humans have a notable capacity to recognize unexpected outcomes from their actions. Schön argues that reflection within the design process holds a unique form of rigor, central to what he terms 'professional artistry,' a stark contrast to Simon's 'technical-rationality' which views design problems as predefined and solvable with scientific precision.

While Simon sought to position design within a scientific framework, Schön highlighted the reflective, nuanced nature of design practice, focusing on the interplay between action

and reflection. This distinction between their viewpoints has sparked discussions, with a consensus that, despite their differences, both have significantly contributed to our understanding of design. Differences between Simon and Schön's views of design have been discussed by several authors (Bousbaci, 2008; Dorst, 1997; Sköldberg, *et al.*, 2013). However, they all agree that, while Simon aimed to create an objective and scientific framework for the field of design, Schön emphasised descriptions of designers in practice.

Schön's design philosophy has faced critique. Greenwood (1993) suggests Schön underestimates pre-action reflection, focusing instead on 'reflection in action,' which prioritizes changing situations over understanding them—a point not universally applicable. Boud *et al.* (1985) claim Schön overlooks the contextual aspects of reflection. Ekebergh (2007), drawing from phenomenology, contends that immediate reflection within a situation is unfeasible, arguing for retrospective reflection as essential for genuine self-awareness. Despite all the criticisms, Shön's approach to formulating design as a reflective activity, and his proposal of the reflective-practice concept, has been an influential proposal approach in describing designers in practice.

2.6.3. Design as Building and Reusing Artefact - Reddy *et al.* (1998)

Reddy *et al.* (1998) propose artefact theory as a framework tailored to specific design contexts, emphasizing the lack of universal design theories and the utility of developing theories for particular artefacts. They describe contextual theories as being crafted through the collection and organization of knowledge within specific contexts. For instance, theories specific to bridge construction or horology are essential for designing and building particular artefacts or artefact classes. These theories can form hierarchical layers, with more foundational theories informing more specialized ones through adaptation and the incorporation of context-specific knowledge.

The motivation behind their theory stems from the insight that design is both a process of using existing knowledge and generating new knowledge. As artefacts are designed, knowledge is built up and systematized, leading to the continuous refinement of both designs and design methodologies. Design, therefore, is seen as creating a manufacturable artefact description, including detailed models, material specifications, and assembly instructions, as well as developing an underlying theory that guides design decisions. This theory generation

involves crafting new concepts and integrating elements from established theories. Reddy *et al.* also illustrate their concept with a graphical model showing how theory construction, sharing, and application interplay within the design process (Figure 2-25)

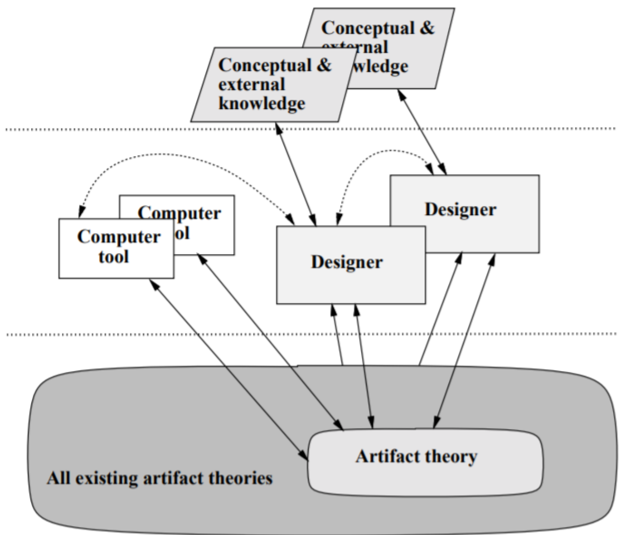

Figure 2-25 Model of design process Reddy et al. (1998)

Reddy *et al.* (1998) argue that designing involves creating and reusing theories specific to artefacts, crucial for understanding and expanding design knowledge. They point out the necessity for design environments to evolve by capturing and reutilizing new knowledge, which many current systems overlook. Such environments should facilitate access to knowledge sources, support knowledge organization and reuse, and encourage collaboration among designers, thereby enhancing corporate memory.

They draw parallels between the progression of physical sciences from separate theories to a unified understanding and suggest design could follow a similar path through contextual theories. Yet, Reddy *et al.* (1998) acknowledge the existing gap in how to integrate these artefact-specific theories into a comprehensive design theory, underscoring the challenge of synthesizing individual design insights into a cohesive framework.

2.6.4. Decision-Based Design

Decision-based design (DBD) is a body of scholarly works that recognises the importance of decision-making in design (Marston, *et al.* 1997; Hazelrigg, 1998; Thurston, 2001; Wassenaar and Chen, 2003; Krishnamurty, 2006, Lewis, *et al.* 2006, Mistree *et al.,* 1990). The umbrella of

DBD research recognises that the core role of a designer is to make decisions. In this paradigm, design is considered a decision-making process subject to a set of rules or governing, rational axioms. Central to DBD is utility theory, which relies on rational behaviour axioms to model decision-makers' preferences, identifying the most rational, unbiased choices based on mathematical models.

This perspective benefits from incorporating established decision-making theories from economics, operations research, and decision sciences into the design process. It integrates engineering design into a comprehensive system perspective, emphasizing the consideration of a product's entire lifecycle and grounding design decisions in value theory (Hazelrigg, 1998). Utility theory, a decision-making approach founded on rational behaviour axioms, has been effectively applied to design challenges. This theory aligns design with foundational axioms akin to those in traditional sciences, constructing mathematical models to elucidate a decision-maker's preferences for identifying optimal choices under rational, consistent criteria (Marston and Mistree, 1998; Mech and Jun, 2001). Utility is defined as a preference function based on axioms by von-Neumann and Morgenstern (1947), facilitating decision-making under risk.

However, this perspective faces challenges, especially in handling trade-offs between conflicting objectives under uncertainty. Thurston (2001) points out limitations in utility analysis during initial design configurations, analytic phases, and group decision-making situations. These insights are summarized in Table 2-8 which provides a detailed classification of the benefits and limitations of DBD and utility analysis, underscoring the complexity of applying decision-making theories to design.

Design Stage	Limitations of Decision Based Design with Utility Analysis	Benefits of Decision Based Design with Utility Analysis
Customer/Designer Need Expressed		Separates true objectives from superfluous Defines true tradeoff range Avoid biases, inconsistencies, paradoxes in customer preferences
Creative Synthesis of Alternatives	Cannot replace creativity Cannot replace engineering expertise	Frees designer to think in terms of function rather than form Defines initial filter for feasible material, configuration, manufacturing options based on attribute and range definition
Analysis	Cannot define analytic constraint equations (strength of materials, kinematics, structural analysis, etc.)	Indicates which analytic equations are relevant, based on attributes and range Indicates where experimentation or other effort is worthwhile to improve analytic model
Tradeoff Evaluation	Cannot determine which tradeoffs are technically feasible (must be done through analysis) Cannot define Pareto Optimal frontier Cannot provide solution procedures, optimization algorithms	Rank orders preliminary alternatives Identifies alternatives worth further analysis Determines which tradeoffs are desirable Focuses effort where payoff is greatest Defines objective function for optimal solution
Decision Making under Uncertainty	Cannot remove uncertainty	Provides method for modeling uncertainty Includes effect of uncertainty on rank order of alternatives Avoids irrationality under uncertainty Determines when it is worthwhile to gather more information vs. when to act, via expected value of information
Team Design	Does not resolve Arrow's Impossibility Theorem	Provides framework for obtaining preference information from individuals and/or group Communicates preference information to team members Breaks decision problem into components on which consensus can be reached

Table 2-8 Limitations and benefits of decision-based design with utility analysis (Thurston, 2001)

Further critics exist, for example, Mech and Jun (2001) argue that decision-based theories in design cannot be directly employed to generate a set of feasible alternative design configurations, nor to perform design analysis. They also add that the theory is unable to resolve the central problems of group decision-making, which are that different voting

methods yield different results. These criticisms show the incapability of this approach to engage with design as a social and cultural phenomenon.

2.6.5. General Design Theory

Yoshikawa and Tomiyama (1981) introduce General Design Theory (GDT) and its extension (EGDT), proposing design as evolving through metamodels. GDT suggests knowledge can be mathematically formalized, based on axioms of recognition, correspondence, and operation, aiming to map functions to attributes ideally. However, recognizing the limitations of ideal knowledge, they acknowledge real design knowledge involves finite, imperfect information, leading to design as a stepwise refinement through metamodels (Tomiyama and Yoshikawa, 1985 & 1986; Thompson, 2011).

GDT assumes pre-existing topological spaces and knowledge mappings, suitable for domains with known structures. Yet, Reich (1995) and Reddy *et al.* (1998) critique this for overlooking the inventive aspects of design, where significant knowledge emerges during the design process. Reich points out the absence of real-world domain structures presumed by GDT and its failure to accommodate the creative expansion of entity concepts.

Braha and Reich (2003) extend Yoshikawa's theory into the Coupled Design Process, addressing design's dynamic, nonlinear, and exploratory nature. Conversely, Hatchuel and Weil (2009), however, argue that dynamic mapping is still not adequate to describe the generation of new objects and new knowledge which are also distinctive features of Design and hence, inappropriate for practical design problems.

2.6.6. Concept-Knowledge Theory

Hatchuel and Weil (2003) introduced the C-K theory or concept-knowledge, as a general theory of design, giving a formal framework for accounting for creativity, learning and innovation in design. The theory is based on the distinction between two expandable spaces: the space C of concepts and the space K of knowledge. As per this theory, once a new concept is created by a designer and C-space is expanded, new knowledge is activated and hence K-spaces are expanded simultaneously. These expansions are complementary: new knowledge provokes the identification of new concepts, and the elaboration of new concepts results in the search process to acquire new knowledge (CK-THEORY.ORG, 2017). Hence, the theory

defines the process of design as the co-evolution of C and K, which is done through four types of interdependent operators: C → K, K → C, K → K, and C → C (Hatchuel and Weil, 2003). The knowledge-to-knowledge (K-K) operator represents classic types of reasoning (classification, deduction, abduction, inference, etc.) whereas the other three operators are more design specific. Moreover, "any design methodology that can be performed as a program (or an algorithm) without any use of concepts and C-sets is finally reduced to a K-K operator (for example, the genetic algorithm for optimizing an engineering system uses only standard calculus and logics)" (Hatchuel and Weil, 2009). A graphical representation of a Design Process using C-K Design Theory is presented in Figure 2-26.

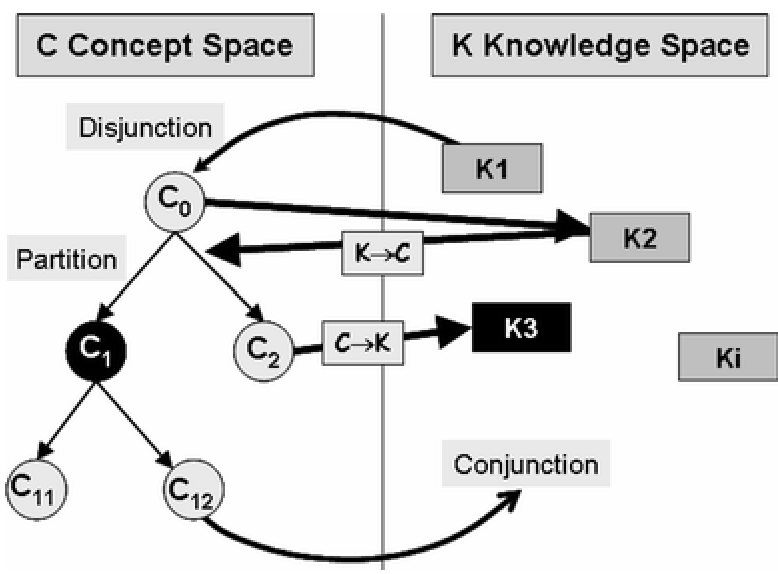

Figure 2-26 Features of C-K theory: Asymmetric structure of spaces C and K (Hatchuel and Weil, 2009)

To elaborate on their theory Hatchuel and Weil (2009) refer to an example of a driver lost in an unknown country, looking for a ''convenient hotel, not too far away and not too expensive''. The driver has no guidebook to the country and has to ask the people he meets for information to help him adjust his own desires to the solutions available". They argue that the driver will not design the hotel where he decides to stay. In effect, what the driver designs is a 'decision function' to find the hotel, as design usually involves far more than selecting existing solutions. Hence, such views of design that consider design as a problem-solving or decision-making process, or dynamic mapping and looking for a dynamic fit between solutions and satisfaction criteria), are not adequate to cover the distinctive aspects of design including the generation of new objects and new knowledge. They note that by introducing new

analytical tools such as concept-sets based on ''K-undecidable'' propositions, the C-K theory offers a framework that provides a formal account of creativity and learning throughout the design process. Kazakçı and Tsoukiàs (2004) suggest that C-K theory "allows for the operationalisation of the concept of 'expandable rationality', which is claimed to be better adapted to design than Simon's bounded rationality.

Despite the consensus in the design community that the C-K theory is one of the very few, and influencing theories of design, it has not been without criticism. One of the criticisms is that similar to the Reflective Practitioner of Schön (1983), the design process is more considered and analysed at the designer level, and more precisely at the designer reasoning level, and hence ignores the collective dimension of design activity and as such unable to organize the complete design and innovation process. In addition, numerous fundamental concepts used in design practice, such as architecture or functions are ignored (Choulier, *et al.*, 2010). As other design theories discussed so far, social aspects are not considered.

2.6.7. Reviewing Design Theories- Conclusion

Table 2-9 presents a summary of the theories reviewed, their essence and the criticisms as presented in the literate. Many of the reviewed theories were criticised as undermining or simply ignoring essential features of the design: taking the problem as given, providing limited or no scope for accounting for creativity, and ignoring social interactions that are needed during the design process. Hence, the table below compares the reviewed theories concerning the coverage of these essential features.

Theory	Essence	Criticisms	Account for creativity?	Social interaction?	Problem exploration?
Sciences of the Artificial (Simon, 1988)	• Define design as a rational problem-solving and logical search for satisfactory criteria that fulfil a specific goal. • Claim that several existing theories can explain different aspects of design and as such articulates the concepts of optimisation, search, evaluation, complexity and representation and introduce the concept of bounded rationality and satisficing about the limited capability of human problem solver.	• Unable to engage with design as a social, political, cultural and creative activity. • leaves small scope for social involvement and creativity. • Assume the goal is defined so limited scope and attention for the problem exploration stage	No, design as rational problem solving.	No, doesn't discuss the complexity of addressing ill-structured and wicked design problems.	No, the problem is assumed as given.
Design as a Reflexive Practice Schön (1983)	• Design is defined as a reflective practice as opposed to rational problem solving where design problems are considered as "given". • The designer constructs the design world within which he/she sets the dimensions of his/her problem space and invents the moves by which he/she attempts to find solutions in reflective conversations with design situations.	• More a description of designers and their thinking approach, rather than a scientific theory of design. • Reflection-before-action and understanding the situation and the initial problem statement have been downplayed.	Yes, the designer constructs the design word.	No, more, description of design thinking.	No, the problem is considered as given.
Design as Building and Reusing Artefact **Reddy *et al.* (1998)**	• A contextual theory of design • Design "not only involves knowledge use but also knowledge building". • Design is a process of constructing a theory of the artefact, not merely constructing a manufacturable description. • While some elements of the knowledge required for design may remain invariant, often many elements are newly developed.	• Contextual: purview of an artefact theory is limited to a single artefact or a set of artefacts and not a general design theory. • More focused on solution development rather than problem setting.	No, more focused on defining artefact-specific theories.	Limited, the role of knowledge sharing is recognised and emphasised.	Limited More focused on solution development rather than problem setting
Decision-Based Design **various))**	• Design is considered as a decision-making process subject to a set of rules or governing, rational axioms.	• The theories that were studied more, e.g., utility theory have focused on solution	No, rational process	Limited, trade-offs are discussed	limited, requirements are considered as given although trade-offs in customer

Theory	Essence	Criticisms	Account for creativity?	Social interaction?	Problem exploration?
	• design decisions account for a product's total life cycle, the designer hence, seeks to maximize the value of a designed artefact. • Many well-developed theories and methods of decision-making from other domains like economics, operations research, decision sciences, etc. can be brought to analyse and understand and advise the design process.	development rather than problem exploration. • cannot directly resolve the central problems of group decision-making, and different voting methods yield different results, related to the inability of the model to engage with design as a social phenomenon.		but not particularly linked to the social aspect of design.	requirements are discussed.
General Design Theory (GDT) (Yoshikawa, 1981) and Extended General Design Theory (EDGT) (Tomiyama and Yoshikawa, 1986).	• Designing is "a mapping of a point in the function space onto a point in the attribute space" however due to finiteness and imperfections in the real knowledge, the mapping is achieved via an intermediate space namely 'the metamodel space'. • the design process as an evolution of metamodels • Design in real knowledge is a stepwise refinement of these metamodels to satisfy the specifications	• GDT assumes the existence of topological spaces prior to design, knowledge about mappings between them, and knowledge about how to mediate between functional and attribute spaces, and hence, only applies to domains with known topological structure. • ignores the creative part of the process including adding new entity concepts.	No, assume knowledge about mapping.	No, there is no notion of addressing ill-structured design problems.	No, assumes the existence of topological spaces prior to the design. Hence specifications are presumed to be specified and fixed in GDT.
Hatchuel and Weil (2003) introduced the C-K theory	• as a general theory of design, giving a formal framework for accounting for creativity. • based on the distinction between two expandable spaces: the space C of concepts and the space K of knowledge. • Once a designer creates a new concept and C-space is expanded, new knowledge is activated and hence K-spaces are expanded simultaneously. These expansions are complimentary.	• Unable to assist and direct the creative process. • design is considered and analysed at the designer level and hence unable to guide the complete design and innovation processes. • Most of the fundamental concepts used, such as architecture or functions, are simply ignored. Social aspects, too, are not considered.	Yes	No, only the designer level is considered.	Yes, implicitly embedded in the expansion of concepts, as the departure point of a design process.

Table 2-9 A comparison of theories of design

The discussion in the previous section shows that design theory is distributed between traditions; however, two dominant themes can be observed within these traditions: first, the paradigm that considers design as an analytic sequence of activity in which all of the elements of the problem and all of the requirements can be determined in advance of developing a solution, and that design problem can be rationally resolved afterwards, and a second paradigm which acknowledges that the actual sequence of design thinking and decision making is not a simple logical and linear process, and that, "the problems addressed by designers do not, in actual practice, yield to any linear analysis and synthesis" (Buchanan, 1992).

The latter paradigm also fed into the wicked problem approach that was introduced by Rittel in the 1960s in response to the rational, stage-based models of the design processes which were popular in the 50s. Rittel argued that most of the design problems addressed are "wicked problems, i.e.: a "class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing." This view presented an alternative approach to design and design thinking "as a social and political problem-solving activity".

Despite efforts to discover the foundations of design thinking in the natural sciences, fine arts, or like Rittel and Buchanan, the social sciences, "design eludes reduction and remains a surprisingly flexible activity" (Buchanan, 1992). This is perhaps one of the reasons why developing a theory of design has proved to be challenging. In fact, apart from C-K theory, which can be categorised as strictly developed design theory, other theories discussed, are imprecise frameworks or propositions for applications of theories in other disciplines into the design research. The lack of a well-established design theory, which is also independent of the object of the design or perspective to design, is recognised within the design community and in fact, the Design Society has formed a special interest group in design theory in response to this challenge.

Hence, empirical studies would be beneficial and can deliver a theoretical contribution to the field of design research.

Despite the limitations and imperfections of the theories reviewed all present commonalities, in seeing design as a human activity, involving some form of search not only

for existing knowledge and solutions (e.g., Simon's science of artificial, or Yoshikawa GDT) but also search to acquire and develop new knowledge (e.g. Reddy artefact theory, or Hatchuel C-K theory). However, still, the existing theories are unable to explain how a particular design emerges considering the complexity, uncertainty and collaborative nature of the design process.

2.7. Holistic Design

For the purposes of this study, it's crucial to define 'holistic design'. The usage of 'holistic' within the design community is not uniform or widespread. To clarify what 'holistic design' means in the context of this dissertation, an examination of the general understanding of 'holistic' and 'holism', in contrast to 'reductionism', will be conducted first. This will be followed by an exploration of how this concept is referenced within design literature. Drawing on this exploration and significantly influenced by the work of Ulrich and Ellison (2010) on defining holistic customer requirements, a definition of holistic design challenges will be established. The Oxford Dictionary defines 'holistic' as being "characterized by the belief that the parts of something are intimately interconnected and explicable only by reference to the whole". The term holistic cognates the word 'holism'; which is normally contrasted with the term 'atomism' or 'reductionism', both quite similar in definition. Atomism refers to "the theoretical approach that regards something as interpretable through analysis into distinct, separable, and independent elementary components" and reductionism refers to "the practice of analysing and describing a complex phenomenon in terms of its simple or fundamental constituents, especially when this is said to provide a sufficient explanation" (Oxford dictionary). "Holism (from ὅλος holos, a Greek word meaning all, entire, total) is the idea that all the properties of a given system (biological, chemical, social, economic, mental, linguistic, etc.) cannot be determined or explained by the sum of its component parts alone. Instead, the system as a whole determines in an important way how the parts behave" (Psychology Wiki, n.d.)

In science, reductionism is usually considered an approach to studying a complex system by breaking it down into simpler parts, looking into them separately, and then "puts them back together" in order to understand the whole. Wilson *et al.* (1988) argue that "the phrase 'puts them back together' can only mean studying the interactions among the parts". He

further adds that despite the frequent statement that "the whole is more than the sum of its parts", reductionists do not expect interactions among parts to be additive.

Often, the entirety manifests in a manner that the individual components alone cannot predict. This perspective emphasises that the whole emerges from the complex interplay among parts within intricate networks of relationships. Jackson (2003) posits, "Once it has emerged, it is the whole that seems to imbue the parts and their interactions with meaning." The holistic approach views systems as entities that transcend the mere aggregation of their components. While it acknowledges the importance of individual components and, specifically, the networks of relationships among them, the focus shifts towards understanding how these interactions give rise to and maintain the existence of the whole. This whole could be anything from an automobile to an organization, or even a strategy (Jackson, 2003).

One criticism of reductionism is that in many cases the whole can take on a form that is not recognisable from the parts. In other terms, the whole emerges from the interactions between these parts, which themselves interact through complex networks of relationships. “Once it has emerged, it is the whole that seems to give meaning to the parts and their interactions” (Jackson, 2003). In contrast, holism considers systems to be more than the sum of their parts. Albeit it is interested in the system components and in particular the networks of relationships between them, but mainly in terms of how they lead to and sustain in existence the new entity which is the whole, whether it an automobile, an organisation or a strategy (Jackson, 2003).

Thinking in the context of design, one might expect to consider holistic design to be about considering the whole product as one interconnected entity, rather than a collection of individual parts. Like the human body, a product is made of numerous elements, but it is only able to function appropriately when all those elements work together towards the same objective. Therefore, in a sense, holistic design can be a philosophy that drives toward the alignment of a system and its components with the end goal of a high-performing product, that seamlessly integrates other aspects like aesthetics, sustainability, and user satisfaction.

In design literature, the term "holistic design" seems to predominantly refer to an encompassing approach towards the methodology of design. The holistic design approach refers to an all-encompassing approach that considers every aspect of a product’s design,

development, and user journey. It aims to create seamless, engaging, and user-centred experiences by taking into account the interplay of visual elements, functionality, content, and context (Interaction Design Foundation, 2016; Gavriluk, 2023). This perspective advocates for a synergetic integration of various elements—visual aesthetics, functionality, user interface, and contextual relevance—aiming to cultivate coherent, engaging, and user-centric experiences.

Contrastingly, within the context of this dissertation, "holistic design" is articulated with a specific focus on the noun aspect, signifying the resultant artifact of the design process. This interpretation shifts the emphasis from the procedural dimensions of design to the tangible outcomes it yields. Herein, "holistic design" is construed as the embodiment of a design solution or artifact that encapsulates a comprehensive response to design challenges, reflecting an intricate amalgamation of all design parameters and constrains to manifest as a coherent and integrated product. This subtle application of "holistic design" within my thesis endeavours to illuminate the artifact as the essence of holistic design principles materialised in physical form.

In the domain of design literature, a pivotal reference to the term 'holistic' can be found in the work of Ulrich and Ellison (1999). They specifically employ 'holistic' within the context of design, addressing it in relation to customer requirements and performance attributes. They argue that in addressing holistic customer requirements, firms may choose to design product-specific components in order to maximise product performance. In this context, they define holistic customer requirements as “those requirements that arise in a complex way from most of the components of a product”. In such systems, the overall performance of the product is governed by “many component parameters that are related to one another in a complex interdependent fashion”. Therefore, the overall design performance cannot be expressed “as an explicit mathematical function” or “can be made only partially explicit”. In addition, “performance of an individual component does not have meaning independent of the product context” and depends on the characteristics of the other components with which it is used. In addition, “each component will typically be characterized by many design parameters, which may need to be tuned arbitrarily to maximize too many possibly useful combinations of component design parameters to be able to enumerate them, and no matter

how many existing components are available, optimal product performance will likely require some new combination of design parameters” (Ulrich and Ellison, 1999).

To elucidate their definition of holistic customer requirements, Ulrich and Ellison refer to a few examples, one reflected in Figure 2-27. The figure shows some of the customer requirements for Aircraft landing gear plotted on the two dimensions that define the degree to which a requirement is holistic. Ride quality is an important customer requirement for landing gear. It is a complex function of most of the components of the landing gear, and can only be partially made explicit, by using numerous coupled parameters and highly non-linear mathematical relationships. Consequently, ride quality cannot be decomposed into independent performance requirements for each of the components. In contrast, is the requirement to minimize landing gear weight. This requirement depends on each individual component and a simple sum function of the weight of each component. “As a result, “good” components from the perspective of overall product weight performance are simply components with low weight - a measure of component quality that does not depend on the other components of the system”. Thus, weight is not a highly holistic requirement.

Ulrich and Ellison (1999) also add that by their definition, requirements that include very complex functions of the product’s design characteristics but do not depend on many components, are also not holistic. i.e., “if a performance requirement depends only on the characteristics of a single component, that component can be optimized in isolation and therefore used with different sets of components without modification”.

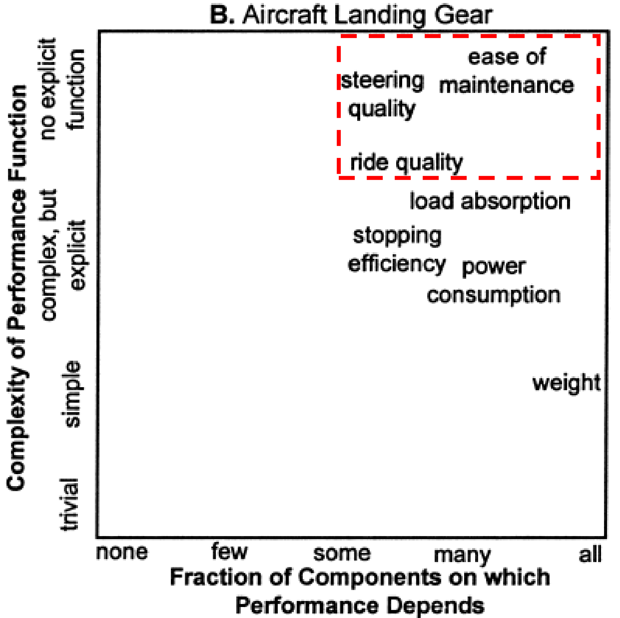

Figure 2-27 Plot of the customer requirements for an aircraft landing gear (Ulrich and Ellison, 1999).

Two key insights emerge from Ulrich and Ellison's examination of holistic customer requirements. Firstly, it is evident that user perception is influenced by a complex interplay of numerous features. Secondly, this perception is inherently subjective and emotive, rather than analytical, as customers typically do not dissect the design into its constituent elements mentally. In essence, the assertion that user perception is shaped 'by most of the components of a product' suggests a multitude of interactions among these components, which are indivisible and cannot be simplified into discrete elements.

To deepen our understanding of the term 'holistic' within the framework of system design, it is beneficial to examine it through the lens of complex system design. Ulrich and Ellison (1999) highlight that in the realm of complex systems, there may be scenarios where the system's performance function is influenced by numerous attributes. This introduces an additional layer of complexity in designing such systems. In essence, to accurately delineate the performance function, its mathematical representation must incorporate all interdependent attributes. This interplay of multiple attributes, which also impacts aesthetic considerations, contributes to characterisation of what this thesis will refer to as 'holistic complexity'.

In the context of holistic complexity, the manner in which a single attribute affects performance is intertwined with the influence of other attributes, meaning the attributes within the objective function are non-separable. For instance, considering a car that is

perceived as both beautiful and fast, its speed may alter the perception of its beauty. This exemplifies the interconnectedness of attributes, a central tenet of holistic complexity.

In addition, in exploring complex system design, it is also beneficial to distinguish between 'holistic complexity' and what may be termed as ‘feasibility complexity’. Holistic complexity captures the scenario where a system's overall performance is not merely dependent on individual attributes but on the synergistic interactions among all attributes. This concept resonates with the holistic view in systems theory, where the focus is on the interdependencies and collective interactions that influence system outcomes.

Contrarily, the complexity arising from feasibility considerations pertains to the fundamental interactions that enable a system's basic operation or existence. It suggests that even if a system's performance ultimately seems driven by a dominant attribute, this attribute's effectiveness is contingent upon a network of supporting interactions among all other attributes. Hence, controlling the performance might boil down to optimizing this key attribute, yet acknowledging that its influence is underpinned by the system's inherent complexity.

Thus, while holistic complexity is concerned with how all parts of a system interact within the performance function, emphasising the non-separability of these interactions, feasibility-related complexity focuses on the system's operational viability. The latter highlights the essential interactions that must occur for the system to function, regardless of how performance is optimised. This differentiation sheds light on the nuanced ways in which complexity manifests in system design, particularly distinguishing between the complexity inherent in achieving optimal performance versus that required for basic system functionality.

Therefore, holistic systems represent a specific category of complex systems wherein the interactions occur directly within the objective performance function. In contrast, other complex systems exhibit a form of complexity derived from the interactions necessary for the system's feasibility.

Consider a Design Structure Matrix (DSM) involving design parameters X1 and X2, illustrating a scenario where the design decision for X1 depends on X2, and vice versa, indicating that X1 cannot be finalized without determining X2's value, which might fall outside a feasible range. This scenario exemplifies what could be termed 'non-holistic complexity,'

where the complexity arises from the technical interdependencies essential for feasibility rather than from an integrative consideration of how various design aspects influence user perception or choice. Therefore, while feasibility complexity concerns the mutual influences among design attributes within the performance function due to constraints on their feasible ranges, it differs from the complexity considered in holistic design, which is often predicated on the subjective, emotive, and irrational aspects of consumer choice.

In other words, feasibility complexity in design occurs when design attributes mutually influence each other within the performance function, primarily due to their interdependent feasible ranges. This differs from situations where consumers cannot differentiate the impact of various design elements on their choices. Feasibility complexity suggests a rational analysis, while the latter scenario implies irrationality, emotional factors, and subjectivity in decision-making.

In practice, engineers frequently address feasibility complexity, focusing on ensuring that design parameters meet functional and operational criteria. However, design, as defined and intended in this thesis (section 2.1), not only requires that a product be functionally viable but also demands that it be aesthetically pleasing. This distinction underscores the broader scope of design considerations, extending beyond mere functionality to encompass aesthetic appealing. Referring to Figure 2-27, the area highlighted by dotted lines is where complexity transforms into holistic complexity.

Reflecting on the comprehensive discussion presented thus far, it has become clear that a significant gap exists within the existing literature regarding the conceptualization of "holistic design" specifically in the context of the end product of the design process. This notable absence highlights a critical need for a precise definition that captures the essence of design outcomes, characterised by their integrated approach to balancing form and function alongside aesthetics and functionality. These outcomes are efficient, practical, and aesthetically compelling, yet the lack of detailed exploration or acknowledgment of "holistic design" as an end product in the literature underscores the necessity for a new definition. Motivated by this void, the following definition has been formulated to provide an encompassing framework.

It articulates the multifaceted nature of design outcomes that are not only comprehensive in their consideration of essential design parameters but also reflective of an interconnected approach to addressing complex design challenges. Consequently, this definition emerges not just as an academic endeavour but as a pivotal contribution to the field, venturing into the previously uncharted territory of "holistic design" with respect to the resultant artifacts of the design process.

> *"Holistic design" view the design solution as an interconnected and integrated whole, where its performance is the result of nontrivial and complex interactions among multiple parameters and components. This conception of design is marked by several defining characteristics:*

- **Indescribable Overall Performance Function:** The collective performance of these designs eludes precise mathematical expression, reflecting the intricate and multifaceted nature of how different elements contribute to the final product.
- **Contextual Significance of Component Performance**: The performance of any single component gains meaning only within the totality of the product, underscoring the interconnectedness of all parts.
- **Interdependent Component Characteristics**: Each component's effectiveness is closely tied to the characteristics of other components in the system, highlighting the need for a holistic approach to design where every element is considered in relation to the whole.
- **Complex Customer Preference Dynamics**: Customer preferences emerge from a complex interplay of performance parameters, indicating that attractiveness and desirability of the product stem from more than just its functional capabilities.
- **Subjective and Emotive Customer Evaluation**: Preference and product valuation are significantly influenced by subjective and emotive evaluations, suggesting that effective design addresses both the analytical and emotional needs of users.
- **Multiplicity of Design Parameters**: Holistic design acknowledges that each component is characterized by numerous design parameters. Optimal product performance is achieved through the careful adjustment of these parameters, often requiring a nuanced and iterative approach to design refinement.

The relationship between holistic design and holistic customer requirements is inherently symbiotic. Holistic design endeavours to fulfil holistic customer requirements by integrating various design elements to achieve outcomes that are coherent, functional, and aesthetically pleasing. This necessitates a design approach that is proportionate to the multifaceted and interconnected nature of design challenges, where optimizing one aspect of the design may affect others in unpredictable ways. Recalling the car example discussed earlier, enhancing the speed of a car might alter its perceived beauty. This instance exemplifies the interconnectedness of attributes that define holistic complexity, reinforcing the notion that attributes within a holistic design are not isolated but deeply integrated. Holistic design, therefore, is a response to holistic customer requirements, aiming to optimize the overall product performance through a process that accounts for the complex interplay of all design parameters.

This discussion emphasises the distinction and connection between holistic design and holistic customer requirements. While holistic design focuses on creating integrated solutions that address complex challenges, holistic customer requirements articulate the user expectations that guide the design process. Both concepts underscore the importance of a comprehensive approach to design, where understanding and optimising the system's interconnected components lead to outcomes that are not only functionally viable but also align with user preferences and expectations.

2.8. Search

Given the aim of this thesis, which is to characterise and explain the 'search' process involved in solving 'holistic' design problems, it is necessary to define search in the context of design.

Describing design as a process of search was first proposed by Herbert Simon in the 1960s and formalised in his book "The Sciences of the Artificial" (first published in 1969). Since then, several scholars (e.g. Cross, 1977; Restrepo, 2004; Ulrich, 2007, Hatchuel, 2002) have debated it. However, despite these scholarly works, it seems that the term "search" is not appealing to the design community.

In his book, Design, Creation of Artefacts in Society, Ulrich (2011), deliberately avoid the term search and prefer to use the word exploration. He mentions, "the term search tends to offend practising designers. For many, it implies weak methods unguided by expertise." As

another example Cross's work (1997) on creativity in design can be referred to, where he also avoids using the term search and argues that in some fields, the 'creative leap' is characterised as a sudden perception of a completely new perspective on the situation; however, in creative design "there might be no unexpected dislocation of the solution space itself, but merely a shift to a new part of the solution space, and the 'finding' there of an appropriate concept"; He further adds that "this is what characterises creative design as exploration, rather than search.

Hey *et al.* (2017) contributed to the discourse on design search and exploration by examining the cognitive processes involved in designers' search for solutions. They highlighted the importance of both systematic search and intuitive exploration in the design process, emphasizing the need for a balanced approach that combines analytical techniques with creative exploration (Hey *et al.*, 2017). Their discussion provides a nuanced differentiation between design search and exploration within the context of conceptual design tasks. They delineate search as a systematic process involving deliberate inquiry and evaluation of potential design solutions. This involves applying analytical techniques, such as problem decomposition and solution synthesis, to systematically explore the solution space. In contrast, Hey *et al.* (2017) characterise exploration as a more intuitive and creative process, wherein designers engage in open-ended experimentation and ideation to uncover novel design possibilities. Exploration entails venturing beyond known solutions and embracing uncertainty, often drawing on tacit knowledge and intuition to navigate the design space.

Furthermore, Hey *et al.* (2017) highlight that while search tends to be guided by predefined goals and criteria, exploration encourages designers to embrace serendipity and unexpected discoveries. This distinction underscores the complementary nature of search and exploration in the design process, with search providing structure and rigor, while exploration fosters creativity and innovation.

Pugh (1991) offered insights into design search strategies and decision-making processes. His work emphasised the iterative nature of design exploration, where designers navigate through various alternatives before converging on a solution. Pugh (1991) advocated for structured methods to guide design exploration, helping designers to efficiently explore a wide range of possibilities before making informed decisions.

Although some scholars have made distinctions between design search and design exploration (Hey *et al.,* 2019), and others, like Ulrich (2011), avoid using the term design search altogether, for this thesis, the term 'search' is deemed appropriate. This decision is particularly influenced by its acknowledgment in other pertinent literature domains such as complexity theory, which closely aligns with the focus of this research.

To solidify this decision and establish a clear definition of search in the context of this study, an exploration of relevant references and concepts from existing literature is warranted below.

2.8.1. Cognitive Search in Human Problem-Solving

Search is a key topic of interest in the study of human cognition. William James, one of the founders of functional psychology, proposed that humans search through memory much the same way as they look through a house looking for a lost set of keys (James 1890, cited in Todd *et al.* 2012). This recognition of similarities between search in physical and information domains has become a salient theme of research in the literature (e.g., Kuhlthau, 1991, Wilke *et al.* 2009, Hills and Hertwig, 2010, Hills and Dukas, 2012, Todd *et al.*, 2012).

Hills and Duckas (2012) studied parallels between human searching across external and internal domains and defined search as:

"an attempt to arrive a goal at an unknown location in the physical environment, as well as in time, memory or any other space".

Hutchinson *et al.* (2012) carried out research aiming at identifying parallels between cognitive search and search in behavioural ecology and highlighted that:

"Essential components of search are a functional goal, uncertainty about goal location, the adaptive varying of position, and often a stopping rule".

To provide a more generic definition of search, Todd *et al.* (2012) note that search is:

"the behaviour of seeking resources or goals under conditions of uncertainty"

They further add that this "requires individuals to achieve an adaptive trade-off between exploration for new resources distributed in space or time and exploitation of those resources once they are found". As such they define search to be "a common and a crucial behaviour for most organisms" and therefore studied by a diverse range of scientific disciplines and

paradigms, e.g., experimental psychologists investigate search in vision, memory, decision making, and problem-solving; neuroscientists study the neural mechanisms of goal-directed behaviour in humans and other animals; theoretical biologists study the characteristics of evolutionary search in high-dimensional spaces (Todd *et al.,* 2012).

Newell and Simon (1972) proposed that human problem-solving can be thought of as searching a problem space, consisting of the initial (current) state, the goal state, and all possible states in between. The initial state is the state at which problem-solving begins. A set of operators, or actions, can be taken in order to move from one state to another. Another element of problem-solving formulation in Newell and Simon's theory is the concept of path constraints, which impose additional conditions on a successful path to a solution (e.g., the constraint of finding the solution using the fewest possible steps). A solution is a sequence of operators that can transform the initial state into the goal state per the path constraints.

All search techniques can be found to belong to one of the two broad categories of search methods: first, brute-force search or exhaustive search, (also known as generate and test, or blind search) and second, heuristic or informed search (Kopec and Marsland, 2001). Exhaustive search consists of systematically enumerating all possible candidates for the solution and checking whether each candidate satisfies the problem's statement. Heuristics are then cognitive shortcuts that guide intelligent search.

Newell and Simon (1972) proposed that human beings, with their limited working memory, are not capable of brute-force search under most problem-solving scenarios. So rather than attempting the impossible task of testing all the possible operator sequences, people only consider a small number of alternatives that seem most likely to produce a solution. In effect, intelligent problem-solving is largely based on using methods for heuristic search. The usefulness of heuristic search depends partly on the nature of the problem to be solved. A key defining factor is whether the best possible solution is required, or whether any good enough solution that achieves the goal will suffice. Therefore, heuristic methods are rarely of any use in 'solving best–solution' problems (Holyoak and Thagard, 1995). Clarke *et al.* (2003) refer to other characteristics that make a problem suitable to be attacked by heuristic search, including large solution space, which makes enumeration of candidate solutions impossible or extremely expensive, and lack of existence of efficient and complete solution, as there may little to be gained by applying a new solution to a problem that is

already efficiently and fully solved, however, he argues that “search based approaches may yield additional insight and may help to ‘fill in gaps’ where existing solutions are partial”. He also adds that in such cases generation of candidate solutions needs to be valuable in a reasonable time.

Simon (1981) proposed that human beings are particularly good at what he calls ‘satisficing’: finding reasonably good but not necessarily the optimal solution.

Different methods of heuristic search exist, some are very general and can be applied to virtually any problem, while others are more specific, and depend on detailed knowledge of a particular problem domain. Heuristics that are commonly used by humans are backup avoidance, difference reduction, and means-ends analysis to guide their selection of operators (Anderson, 2015).

Backup avoidance or repeat-state avoidance is the simplest heuristic, whereby problem solvers prefer not to take an action that would take them back to a former problem state. This approach is not helpful when an individual has taken an incorrect action and needs to turn back a step or more.

Another heuristic is Hill-Climbing or difference reduction, this is particularly used in unfamiliar domains, whereby individuals try to reduce the differences between the current state and the goal state and hence take the action that leads to the biggest similarity, between the two states.

Means-ends analysis is a more sophisticated method of operator selection. This method was extensively studied by Newell and Simon (1972), who used it in a computer simulation program (called the General Problem Solver—GPS) that models human problem-solving. It involves creating sub-goals (end) to enable the application of a desired operator (means). Like difference reduction, the means-ends analysis heuristic seeks the action leading to the greatest reduction in the difference between the current and the goal states but also determines what to do if that action cannot be taken. In other words, if the desired operator can be applied, it will be and if it cannot, a new goal is set to reach a state that would allow the application of the operator. Anderson (2015) notes that “by using means-ends analysis, humans and other higher primates can be more resourceful in achieving a goal than they could be if they used only difference reduction”.

In addition to the concept of 'Search', Abstraction and Representation are other key concepts, which need to be reviewed in the discussion of the cognitive process of human problem-solving. These concepts will be discussed in detail in section 2.8.3, and relate to the cognitive process to simplify problem space by building mental models of the space which are less rugged. Ulrich (2011) mentions that representation is a language for describing solutions using symbols. He also adds that representation requires abstraction which is a limited description of the problem/solution (e.g., sketches are used to represent a design solution, musical notation to represent a song, flowcharts to describe a software program or a service, etc). VanLehn (1988) argues that representation should follow a process of problem comprehension. i.e. understanding the problem is the preceding step in the problem-solving process. He notes that problem-solving behaviour has two components: understanding and search. Reitman (1964) proposed that the difficult part of some problems is not search but formulating the problem, to begin with. He mentions that problems exist in the head (or more generally, memories) of particular problem-solving systems and of course, they need to be represented in order to be solved. However, although representing a problem is a crucial part of solving it, but it is only the result of comprehension processes. A well-structured problem is one that has been formalised by the problem-solver (Simon, 1973). In this regard, the formalisation process, which is also referred to as comprehension in the literature, is a key part of creating a problem representation. VanLehn (1989) notes that understanding does not run to completion before the search begins, but the two processes alternate and even blend together (cited in Quesada *et al.*, 2005).

Hey *et al.* (2017) also note the importance of Schema Activation and Information Processing in problem-solving activities. They argue that individuals engage in the retrieval of schemas from their long-term memory that are relevant to the problem at hand. These schemas represent complex knowledge structures that incorporate both declarative knowledge about the problem's characteristics and procedural knowledge detailing the steps or operations required to transition from the current state to the desired outcome. This approach to problem-solving suggests that effective navigation through problem spaces is not solely reliant on heuristic search strategies. Instead, it also involves the activation and dynamic manipulation of these intricate knowledge structures. This process is fundamental to human cognition, enabling individuals to apply a rich tapestry of previous experiences and

learned strategies to novel situations, thereby facilitating a deeper and more nuanced exploration of potential solutions.

To summarise, the search theory of problem-solving proposes the following about human cognition:

- Problem-solving involves search through a space of candidate states that are generated from other states by applying operators.
- Abstraction and Representation of problems are key elements of human problem-solving (this will be further discussed in section 2.8.3), but these only follow a process of problem comprehension. Understanding the problem also does not run to completion before the search begins.
- Human problem-solving is largely based on using methods for heuristic search, i.e. rather than carrying out an exhaustive search through problem spaces, humans use heuristics to guide selective search.
- Problem solvers often utilise means-ends analysis to organize their search. This process finds differences between current and desired states, selects operators that reduce the differences, and applies the operators or creates subtasks to make them applicable.
- During the problem-solving process, problem solvers retrieve schemas relevant to the problem from their long-term memory. This suggests that human problem- not only involves heuristic search but also the activation and manipulation of complex knowledge structures to navigate through the problem space effectively.
- Human beings are capable of 'satisficing': finding reasonably good but not necessarily the optimal solution.

2.8.2. Bounded Rationality in Information Processing

Before discussing search in other areas of literature, a discussion of a few concepts, related to human problem-solving, would be beneficial. One is the concept of bounded rationality as introduced by Herbert Simon (1957). The term first appeared in Simon's book Models of man, social and rational, and was advanced much by him and other scholars (e.g. Nelson and Winter, 1982; Elster, 1983; Selten, 1990; Gigerenzer, 2001). However, yet the concept of

bounded rationality is firmly associated with Simon’s name (Barros, 2010). Simon presents a very clear and comprehensive definition of bounded rationality as below:

> “Bounded rationality is simply the idea that the choices people make are determined not only by some consistent overall goal and the properties of the external world, but also by the knowledge that decision-makers do and don't have of the world, their ability or inability to evoke that Knowledge when it is relevant, to work out the consequences of their actions, to conjure up possible courses of action, to cope with 'uncertainty (including uncertainty deriving from the possible responses of other actors), and to adjudicate among their many competing wants. Rationality is bounded because these abilities are severely limited. Consequently, rational behaviour in the real world is as much determined by the "inner environment" of people's minds, both their memory contents and their processes, as by the "outer environment" of the world on which they act, and which acts on them (Simon, 1999).

For Simon, more specifically, the notion of bounded rationality is built through the following steps: People or organizations often follow multiple objectives, which may be conflicting. Decision alternatives to choose in order to pursue these objectives are not given in their entirety but must be discovered through a process of search. The limits in the decision maker's cognitive capacity relative to the complexity of the decision environment are already present at this search stage and usually prevent the decision maker from seeing the full set of alternatives. Those limits are also present when the actor needs to evaluate the consequences of the alternatives and prevent him/her from identifying the causal linkages between possible alternative actions and possible outcomes in full. Hence, the decision maker employs some heuristic procedure for that purpose. Finally, the actor takes on a "satisficing" strategy rather than optimising, searching for solutions that are "good enough" or satisfactory, given some aspiration levels. An aspiration level is a value of a goal variable that must be reached or exceeded by a satisfactory decision alternative. This is in line with Simon’s description of decision-making as a search process guided by aspiration levels. Satisficing is often seen as the essence of bounded rationality. However, there is more to it than just finding something that is ‘good enough’. “Aspiration levels are not fixed once and for all, but dynamically adjusted to the situation. They are raised, if it is easy to find satisfactory

alternatives and lowered if satisfactory alternatives are hard to come by". (Simon 1957, cited in Selten, 1999).

The above-mentioned features characterise Simon's view of bounded rationality: Search for alternatives, use of heuristics to choose alternatives for consideration, satisfying, and aspiration adaptation.

Simon (1995) also discusses the concept of bounded rationality in the context of design process. He describes design as a process of search, and of the discovery of new information about available alternatives and about the consequences of choosing those alternatives. He further notes that design is also a process for discovering the goals to be achieved and the constraints to be satisfied. "Goals and constraints are no more fixed elements in design than is anything else" (Simon, 1995). In line with his definition of design, he mentions that design process is formed in fundamental ways by the fact that human rationality is bounded and shaped especially by the very narrow focus of human attention. In this respect, he identifies three ways, all critical for the process of design, in which human rationality is bounded:

- "we know only an infinitesimal fraction of the things we need to know (the things that are relevant for arriving at an optimal design."
- "our computational powers allow us to compute only a few of the innumerable implications of the things we do know"
- we store what we know in that part of the brain that is usually called "long-term memory." Other parts of our knowledge are stored in external encyclopaedias and reference sources, like paper and increasingly in computer memories, only the index to the information being held in memory. The long-term memory is also indexed and is accessed by the process we call recognition. "Some stimuluses in the external environment a word on a page, a picture, an object gives us access to information already stored in memory about that kind of word, picture, or object. We say that we recognize it. Now, this method of information storage imposes severe limits on us. We can only recover the information that is indexed and that is cued by recognition. And we can only look at one page of the encyclopaedia at a time. We may have a vast amount of information potentially at our disposal, but only a small fragment of it

whether stored internally or externally can be in our focus of attention at any one moment".

Elster (1983) mentions that in addition to the cognitive limitation of one's mind, the rationality of individuals is limited by their formal training, experience, skill, and the finite amount of time they have to make a decision, and hence it is impossible to comprehend and analyse all of the possibly relevant information while making choices.

Therefore, bounded rationality and the concept of satisficing explain how people make a decision when optimisation is out of reach.

2.8.3. Offline Vs Online Search

The discussion in the previous subsections highlighted the importance of interpretation and cognitive representation of the problem situation. Such cognitive representations are a critical determinant of human choices and actions (Tversky and Kahneman, 1986; Fiol and Huff, 1992, Thagard, 1996, Gavetti and Levinthal, 2000).

To interpret their environment, rationally bounded actors, build an imperfect cognitive representation of their environment. All human thinking then works within this incomplete model of reality. Such representations are done to simplify the complexity of spatial, temporal and causal relationships between choices, and choices and actors. Cognitive representations are therefore of lower dimensionality than the actual landscape and hence are also known as the abstraction of reality. This assumption of low-dimensional cognitive maps is consistent with arguments in the cognitive psychology literature (Johnson-Laird, 1983; Halford *et al.*, 1994).

Gavetti & Levinthal (2000) mention that building a simplified cognitive map of reality provides the intelligent actors with "a small set of focal alternatives corresponding to the relatively few local peaks on the cognitive landscape and thereby provide a powerful direction for individual choice processes". The cognitive representation, while still grounded in the actual landscape, tends to be less rugged, or multi-peaked, than the actual underlying fitness landscape as the result of the simplification process. In addition, building a simplified cognitive representation of the landscape provides the agent with an opportunity to spot the point in the landscape to move directly to and from there start the usual local trial-and-error search.

The process of cognitive representation is also referred to as a forward-looking search or offline evaluation in the literature. Building cognitive representations or mental models are hence critical steps in decision-making that highly impact the outcome of the search and the consequences of proposed actions for searching.

After the search starting point has been defined using this mental model of reality, the experimental part of the search begins. This stage of search is also referred to as "backwards-looking" (vs forward-looking) and "on-line evaluation" (vs off-line evaluation) and all refer to "choice processes in which knowledge of the linkage between actions and outcomes is derived on the basis of actions taken". While the process of offline search is "limited by one's representation or mental model of the world", online search is constrained by the "limited number of experiences that one may have relative to the vast set of possible actions that one may take" (Gavetti & Levinthal, 2000)

Intelligent search is driven both by cognitive offline search as well as by experimental online processes. Where cognition is a forward-looking form of intelligence and is based on an actor's beliefs about the linkage between the choice of actions and the subsequent impact of those actions on outcomes. Such beliefs derive from the actor's mental model of the world (Holland *et al.*, 1986); While, whereas the experimental search is based on trial and error and adaptation. Thus, in solving problems the intelligent agents are seen as both forward- and backwards-looking (Gavetti & Levinthal; 2000)

Darke (1979) discussed the concept of comprehension and offline search in the context of design. She proposed that designers interpret the design situation through images of the possible solutions and called these preconceptions "the primary generator of design". She mentioned, "these preconceptions seem to act as points of departure in the development of a design concept. When confronted with a new design situation, the designer imposes images of possible solutions to it. These images provide a means for the designer to analyse and structure the design situation, thus directing the actual development of the product form. Restrepo and Christiaans (2004) argue that preconceptions do not have to be only in form of images of the (possible) solutions but could also be abstract relations describing the design situation. In any case, such early representations have a great impact on problem structuring and how the design evolves.

Ulrich (2011) also describes the process of interpretation, abstraction, and representation in design problem-solving. He notes that designs can be represented using symbols that are easily understandable by humans. For example, designers use sketches as a representation of the geometric form of artefact and humans, designers more specifically, are quite adept at interpreting such sketches. Such representations, however, need to be abstract, i.e., include only the essential information about a possible artefact. He notes that "good abstractions suppress details that have little relevance for the central design decisions at hand" and are required to manage the cognitive complexity of the design.

As well as reducing the complexity of the design space by focusing attention on the core design decisions, Ulrich (2011) highlights that "representations are used to record design alternatives in external memory. Humans do not have the cognitive ability to store and recall the dozens or hundreds of alternatives typically explored during the design process. In contrast, paper, digital files, and physical models are quite effective storage devices for that task". What has been just mentioned is also related to Simon's concept of bounded rationality discussed in the previous section.

Ulrich also distinguishes a third function for representation and abstraction and that is to help in the exploration of the non-physical domain. For example, to design a shed without using sketches or similar means to represent its form, one just would need to start building it. Hence representation helps in moving away from searching the physical world with the actual construction materials of artefacts, which is not possible or preferred in most domains as the cost in time and materials of building the design solution directly is quite high. This functionality of representation and abstraction is similar to the concept of cognitive offline search, which was discussed earlier.

To summarise the concept of offline or cognitive search plays a key role in search in problem-solving in different ways:

- Help the problem solver to build simplified models of the world; this simplification on its own enables the agent to first, focus attention on the core decisions that need to be made, and hence decide on points of departure in developing the solution; and second, think about the linkage between the choice of actions and the subsequent impact of those actions on outcomes.

- Helps to manifest alternative solutions in external memory; this manifestation of information and possible solutions externally, again helps the search process from different perspectives: first, helps the rationally bounded agent to recall and analyse information and second enables the agent to postpone the online search as much as possible as experimental part of the search is time and resource consuming.

2.8.4. Search Strategies

In previous sections, a few heuristic strategies, used in human problem-solving were discussed. It was discussed that heuristics that are generally used by humans for guiding the problem-solving process are backup avoidance, difference reduction, and means-ends analysis. It was mentioned that means-end analysis is more commonly utilised to organize search where more flexibility is required due to a high level of uncertainty resulting from a lack of information about the search domain, or where more resourcefulness is required.

In the context of design problem solving, Ulrich (2011) highlights four search strategies that are used to manage the complexity of the search, namely hierarchical decisions (or sequential decision strategy); parallel exploration and selection, causal relationships and existing solutions:

Hierarchical decisions (serial search)

“Subsequent design decisions can proceed sequentially” (Ulrich, 2011) and by doing so search can be a process of choosing which avenues to take at each decision point. Ulrich adds that this approach does not guarantee that the best alternative is found on the first pass undertaken. Also, it cannot be known that there is not a better design down some path that was not explored. Consequently, in most cases, designers will search several paths, may go backward, and may explore several different sequences of decisions. In any case, a series of promising designs can usually be created fairly efficiently by considering decisions hierarchically (serially or sequentially).

In effect, hierarchical decision-making is similar to the concept of serial search which is a well-known search algorithm used by design engineers to iteratively find solutions to complicated design problems. Serial search includes successive iterations, each depending upon the step before it. The basic question in serial search is: “what shall be done next?” Therefore, the search learns what avenues to follow and which ones to abandon by measuring

how close the current iteration is to the solution. "Therefore, some possibilities will never be generated as they are measured to be less likely to complete the solution" (Newell and Simon, 1976).

This strategy has also been widely discussed in other areas including project management, product development and organisational development (e.g., Pich et al. 2002; Sommer and Loch, 2004) but mainly referred to as "trial and error learning". The approach refers to an unplanned (as opposed to planned) adjustment of the problem-solving activities and targets to emerging new information. Therefore, the strategy gives the search agent the flexibility to modify its behaviour as new insight and information are acquired. Sommer and Loch (2004) note that the ability to make adjustments to new information is key to this approach; three sources for new information are acknowledged in the literature: first, information is actively gathered (Miller and Lessard 2000, Thomke, 1998); second, new information is screened for, e.g., by paying attention to the sensation of surprise as a signal of new information (Isenberg, 1984), and third, information is recognised and admitted as something unexpected (Weick and Sutcliffe, 2001).

Ulrich (2011) mentions that when this approach is used, design decisions can be arranged in order of decreasing importance and order of increasing effort and the designer can focus on the high-impact, low-cost decisions first, and defer the high-cost, low-impact decisions for later.

The learning and knowledge creation aspects of serial search make this approach more favourable in circumstances where the search agent deals with novel situations with a high degree of unforeseeable uncertainty (Chew *et al.* 1991; Lynn *et al.* 1996; Sommer and Loch, 2004)

Parallel search and selection (Selectionism)

Parallel exploration and selection, also known as selectionism, involves pursuing several trajectories of decisions independently of one another and picking the best one. McGrath (2001) suggests that Selectionism assumes that "success depends upon generating enough variations that at least some will prove ex-post to yield desirable results". In a parallel search, choosing trajectories at each decision point, avenues are selected that are more likely to produce desirable outcomes.

Ulrich (2011) suggests that in design, the trajectories are followed “only as far as necessary to make an assessment of the likely quality of an artefact that would result from pursuing the trajectory fully. The designer in effect walks down a path only far enough to get a sense of how the landscape looks in that direction. By exploring several alternative paths in a preliminary way, the designer avoids wasting resources refining a design concept that will ultimately prove unsatisfactory” (Ulrich, 2011). The multiple trajectories can be explored by individual designers, or several designers that are part of a team, or even in a tournament, the latter one is popular in the automotive design industry.

Therefore, design search can be divided into a selection phase, which includes exploring alternatives, and a development phase including more online or experimental search which is more costly.

Sommer and Loch (2004) suggest that when unforeseeable uncertainty is present and excluding the cost involved, trial and error learning may offer a systematic solution advantage over selectionism. The reason is that, in practice, most tests that are conducted to select amongst alternatives are imperfect, they take place in a controlled and confined environment “missing some aspects of technical implementation or of the customer usage environment. A truly perfect test typically requires a full market introduction”.

Causal relationships

The most essential cognitive skill required to solve problems is casual reasoning (Jonassen, 2010). Problems are made of factors or elements that are related causally. Knowing and uncovering the causal relationships embedded is essential for solving them. Jonasson (2010) suggests that the purposes of casual relationships are making predictions, implications, interference and explanations. Prediction is a form of reasoning that form a condition or sets of conditions or states to the possible effects that may result from those conditions or states of events. In other words, predictions are probabilistic relationships between cause and effect. Predictions are normally used in forecasting an event or testing a hypothesis for experiments. Implication is a less deterministic form of prediction and “involves identifying anticipated or unanticipated consequences from a causal antecedent”. For example, when a new law is introduced in society there will be some intended outcomes but some unintended social, political or economic outcomes. Hence, implications of events cannot be predicted with confidence. Jonasson (2010) suggests that implication has received little attention in

literature hence little is known about this form of reasoning. Interfaces are required when reasoning backwards from an effect to the cause is needed. A key function of interfaces is diagnosis, which is the identification of the cause or the reason for something else that has happened. The fourth function of casual relationships as noted by Jonasson (2010) is explanation; Jonasson suggests that explaining a system requires awareness beyond what the system is made of but knowing and understanding the interrelationships among the parts of a system and the causal relationships between them. However, it should be noted that explanations of events cannot take place without the ability to predict, implicate and infer.

Expert problem solvers normally have a good idea about the causal relationships between phenomena. Ulrich (2011) mentions that designers normally have a good knowledge of the causal relationship between a particular value of a design variable and the final quality of the artefact. Therefore, decisions about design variables are not made arbitrarily. He adds that casual relationships do not need to be mathematically perfect or valid under all conditions. In effect, they are a form of heuristics that allow more promising designs to be generated efficiently. For example, one heuristic is to use the ratio of 1.6 (known as the golden ratio) for the ratio of the length to the width of the floor. This is not albeit universally valid but provides heuristic instruction that often leads to better solutions.

Causal relationships are learned through experience, and in fact, knowledge of these relationships is one of the important factors that differentiate novices from experts as they approach design problems (Ulrich, 2011). Causal relationships once uncovered and understood, can be modelled and formulated and hence guide the problem-solving process. A study by Fleming and Sorenson (2004) of the patent literature showed that design in domains for which such relationships have not been discovered, learned, or developed is extremely difficult. Schrader *et al.* (1993) suggest that in situations where recognising and articulating relevant variables and their functional relationships is not possible, the problem solver will face ambiguity, or as termed by Sommer and Loch (2004), unforeseeable uncertainty.

Having an awareness of the causal relationships amongst design variables and the ultimate quality of the design solution, and applying heuristics based on such causal relationships lets the designer eliminate the entire design space and focus on a limited area and therefore lead to the development of more successful alternatives, reduced testing

requirement and hence a more efficient design search process. *So, in effect, a causal relationship is not a search strategy for exploring the search space per se, but more a strategy to narrow down the space.*

Existing solutions

Existing solutions are known areas of the search landscape and are of extreme value for problem solvers. Ulrich (2011) suggests that by considering the solutions that others have designed to address a similar problem, the search agent can start the search process with significant knowledge. In fact, if an existing artefact is close to being satisfactory, it can turn into a starting point for incremental adjustment and learning. In addition, as discussed in section 2.8.1, where partial solutions to a problem exist, search will be employed to provide additional insight and help in filling the gap between the partial solution and an acceptable one.

Ulrich (2011) notes that templates are, in fact, generalisations of successful existing design solutions. He refers to a study by Goldenberg and Mazursky (2002) that provides compelling evidence for the power of relatively few templates for guiding the creation of high-quality artefacts in the domains of product design and advertising. They have shown that these templates can be taught to professionals and used efficiently to create new product and advertisement concepts (Cited in Ulrich, 2011)

Eckert and Stacey (2000), mention that “almost all design proceeds by transforming, combining and adapting elements of previous designs”, however, they acknowledge that as well as existing design elements and aspects of other objects, images and phenomena can be inspirational for designers.

On the other hand, research suggests that different forms of prior knowledge, which include not only prior solutions but also previous interpretations of the problem and methods for developing solutions (as per Crilly, 2015), might have both positive consequences (in terms of inspiration) and negative ones (in terms of fixation), according to Crilly and Cardoso (2017). They suggest that by being aware of and addressing fixation, designers can more broadly explore potential solutions. They emphasize the need for strategies to balance being inspired by existing designs with avoiding undue influence that stifles creativity, thereby impacting how designers explore the design space.

Like the causal relationship, exploiting existing solutions to guide the search process is not an approach for conducting the search itself, *but more a strategy to decide where to start the search from, or limit the search space.* In fact, as theoretically proved by Pich *et al.* (2002) serial search (trial error learning) and Selectionism (parallel trials), or a combination of these two approaches are fundamentally the only two search strategies available.

In summary, different strategies can be employed by search agents to first, limit the search space second, decide on the search starting point and third, conduct the search.

Conducting the search is done through two fundamental approaches of learning and selection.

Limiting the search space and deciding on the search starting point seems to be mainly based on using existing information, which can be from the experience of the designers or inspiration from external sources. This is in line with Newell and Simon's (1976) discussion of the source of information in human search, which is either remembering information or extracting information from the domain.

In an ethnographic study of the knitwear design process, Eckert and Stacey (2000) observed that "Skilled designers in visuospatial fields, have very strong visual memories and are also usually very good at generating rich and detailed mental images of designs". Generation of mental images as discussed earlier is an approach to simplify and represent the search space, and a fundamental part of complex problem-solving.

The concepts of existing solutions and causal relationships, identified as search strategies by Ulrich, also bear a significant relation to Schema Activation and Information Processing (Hey et al., 2017). These strategies, when considered through the lens of schema theory, illustrate a fundamental aspect of how knowledge is structured, accessed, and utilised in problem-solving processes. Existing solutions provide a tangible framework of reference that enriches the problem solver's schema with specific instances of successful implementations, embedding a rich tapestry of declarative knowledge within. Meanwhile, understanding causal relationships deepens the procedural knowledge embedded in these schemas, offering insights into the 'how' and 'why' behind the solutions' effectiveness. When activated, these enriched schemas enable individuals to process information more efficiently, guiding the search for solutions through a landscape informed by previously identified relationships and

solutions. This interconnectedness underscores a nuanced approach to problem-solving, where the assimilation of external knowledge into cognitive schemas enhances the ability to navigate complex problems effectively, illustrating a sophisticated interplay between external search strategies and internal cognitive processing mechanisms.

2.8.5. Defining Search in the Context of Design

In the preceding discussions, it has been established that the concept of search extends beyond mere information retrieval, being deeply embedded within the cognitive mechanisms employed by humans for problem-solving. This includes the heuristic approaches utilised for navigating challenges, which are underscored by the constraints of bounded rationality—a concept that captures the limits imposed on our decision-making capabilities by the finite nature of our knowledge and cognitive resources. The intricacies of search strategies have been thoroughly examined, with their crucial role in navigating the complex landscape of information processing being highlighted.

The discussion demonstrated that, design search emerges as a cognitive endeavour aimed at navigating uncertainty with incomplete data, leveraging heuristic methods to manage complexity and guide decision-making. This approach allows designers to strategically find 'good enough' solutions that fall within the bounds of rationality and the resources available. The remainder of this section will delve into the various characteristics of this search process, derived from the preceding discussion in this chapter, aiming to articulate a definition of search within the context of design.

- Design involves search for and *discovery of new information* about the goals to be achieved, the constraint to be satisfied, available alternatives and the consequences of choosing the alternative.
- Design search is *a cognitive problem-solving process* that relies heavily on heuristic methods (for making quick decisions based on simplified principles) and schema activation (to apply existing knowledge structures to understand new information). Both schema activation and heuristics are mechanisms that our cognitive system uses to reduce complexity and facilitate understanding and decision-making.
- The design process is formed in fundamental ways by the fact that human rationality is bounded, not only by having incomplete information of the problem/solution space

but also by their limited availability to retrieve the information that is known, as well as limited computational powers that restrict analysis of implications of the choices made. The generation of candidate solutions for a design problem also needs to be achieved in a reasonable time. Therefore, designers are not only bounded by their limited cognition and information available, but by other factors such as time and budget. Hence, *design search is an attempt to arrive at a goal under conditions of uncertainty and conducted under incomplete information.*

- *In many domains, design problems cannot be fully formalized and subsequently analysed due to the overwhelming number of parameters and discrete alternatives. Even if these problems could be formalized, the mathematical complexity would be enormous. Moreover, human beings, with their limited working memory, are incapable of conducting a brute-force search under most problem-solving scenarios. Therefore, an individual can only consider a limited number of alternatives that appear most promising for finding a solution. Consequently, no method offers a full analysis or guarantees convergence to an optimal solution.*
- In design, *search strategies* are used for conducting the search itself (trial and error learning and selectionism) as well as deciding on point of departure and limiting search space (e.g., causal relationship, and existing solutions)
- Search also requires individuals to achieve an adaptive trade-off between exploring for new resources distributed across space or time and making the most of those resources once found, all within a framework of competing constraints.
- To interpret their environment, designers, acting as rationally bounded actors, construct a highly imperfect cognitive representation of their surroundings. This representation is of lower dimensionality than the actual landscape, serving as an abstraction of reality.
- Designers employ various mediums to represent their ideas, thereby simplifying and formulating the problem. This process enables them to decide on starting points for the development of a design concept and to externally record their interpretation of the problem and potential solutions.

- After conducting an offline search of the design space, designers begin the more time- and resource-intensive process of experimental search. This involves parallel explorations of a few design solutions and/or a trial-and-error approach, featuring gradual refinement of potential solutions.
- Human beings are capable of 'satisficing'—finding reasonably good solutions that are not necessarily optimal. Moreover, in many instances, the criteria for satisficing conclude the search for a design solution; that is, the design process is finalized once a satisfactory solution is identified.

Considering the discussion above, design can be understood as a search process. Within the context of this thesis, the term 'search' is defined as follows:

> ***A cognitive, human problem-solving process, under incomplete information where no method of full analysis or guaranteed convergence is available.*** *The incompleteness of information implies seeking resources or goals* ***under conditions of uncertainty.*** *In such situations,* schema activation and heuristics *search approaches are employed to* ***reduce the complexity*** *of the task, manage the complexity of the search,* and facilitate quick understanding and decision-making. *Search spaces in such cases arise from* ***competing constraints that have to be balanced against one another****. The heuristically* ***guided search*** *terminates when a 'good enough' solution has arrived, and* ***satisficing criteria are fulfilled****.*

It should be noted that the above expression serves solely to clarify the meaning of the term 'search,' rather than the entire design process. While the definition characterises search as a human problem-solving process and design as a form of search, it is not intended to suggest that human search occurs only after the design problem is established. Indeed, as recognised in the design models and theories discussed in this thesis, the cognitive problem-solving process, defined as search herein, is necessary to identify and define the problem before any attempt is made to resolve it.

2.9. Kauffman's NK Model

In previous sections, it was discussed how the search theory of problem-solving explains the process and strategies used in addressing complex problems by rationally bounded humans. One of the influential contributions to search theory is the NK model, which was originally developed as a model of the biological evolution of complex organisms (Kauffman and Levin, 1987; Kauffman, 1989 & 1993; Kauffman and Johnsen, 1991). "The NK model provides a framework to elaborate on Herbert Simons's influential ideas on bounded rationality, computational complexity and near decomposability" (Frenken, 2006). The rationale for the review of this model in the literature lies in its perceived insightfulness regarding design search, the role of designers, required design trade-offs, etc., as well as its rich metaphors and terminology, all of which contribute to its overall informative nature in guiding the analysis of this thesis.

In the biological model, the complexity of organisms is driven by the interdependency in the functioning of genes. Similarly, complexity in a social or technological system can be related to the interdependent working of constituent elements. It has been this similarity which became the basis for transferring the NK Models from biology to other academic realms, including physics (Weinberger, 1991; Kauffman, 1993), artificial intelligence (Reidys and Stadler 2002), the economics of innovation (Kauffman and Macready, 1995; Frenken *et al.* 1999a; Kauffman *et al.* (2000), McCarthy (2003)), organisation theory (Kauffman and Macready (1995), Levinthal (1997), Gavetti and Levinthal (2000), Frenken and Valente (2004)), Industry evolution (Lenox *et al.* 2006; Lenox *et al.* 2007), product modularity (Ethiraj & Levinthal, 2004), product development (Mihm *et al.* 2003) amongst others.

The original model is described in the language of genetics and has two key parameters, N and K, where N represents the number of genes in a genotype and amino acids in a protein or generally components in a given system and is characterized as a string of N binary digits in the model. K is a measure of epistatic links across elements or in biological terms the richness of interdependencies between genes in the genome.

In other words, the K value defines by how many elements each element in a system is affected. Specifically, K represents the number of other elements in the system that affect the effectiveness or fitness value of each component (the concept of fitness will be discussed

later in more detail). Thus, the value of K can range from 0 to N-1. Systems without epistatic links (K=0) have minimum complexity, and systems in which all their elements are epistically related have maximum complexity and the highest K value (N-1).

Kauffman incorporates another parameter in his model, A, which is the number of alleles, the alternative forms or states that a gene (or an element of a system) may have. For a system comprised of N components, the number of possible configurations of the system grows exponentially in N. To define and demonstrate the model Kauffman (1993) restricts A to two, therefore 2^N system configuration is possible; when A is unrestricted, however, the total amount of possible systems configurations/genotypes is A^N.

The model has two principal features: a stochastically generated fitness landscape, on which "higher peaks" correspond to better solutions or combinations of components, and the agent(s) that search a given landscape in order to improve their "fitness" (performance).

These two features are further delineated below.

2.9.1. Fitness Landscape

Kauffman's concept of fitness landscape roots in the metaphor of 'adaptive landscape' which was first introduced by Sewall Wright in 1932. Wright (1932) recognised that epistasis (interactions between genes) makes it possible for a genetic population to evolve toward different combinations of alleles, depending on its initial genetic composition. He invoked the metaphor of a landscape with multiple peaks, in which a population would evolve by moving uphill until it reached its local fitness peak. This metaphor of the 'adaptive landscape' or 'fitness landscape' then became a general term for describing multiple domains of attraction in evolutionary dynamics. (Altenberg, 1996).

Kauffman and Levin (1987) modified this concept by taking into consideration some criticisms of the adaptive hill climbing analogy of Wright's model to develop a general theory of adaptive 'walks' via fitter variants in combination processes; they also introduced the concept of 'rugged' (fitness) landscape. The fitness landscape is rugged when N and K are large, and is smooth and contains only one peak when K is zero (Gerrits, 2014)

The fitness landscape has to be searched by agents in an attempt to find the higher peaks, and the higher peaks represent a better fit. Putting that into the problem-solving language,

the landscape is a space of alternative solutions for a problem. Any alternative consists of N attributes (binary in the simplest form, so that the possibility space adds up to 2N) that influence the performance or payoff of a solution. In terms of a design problem, attributes describe the behavioural properties of components, and components take the physical constituents of a design.

Agents search the space for finding those combinations of components that result in higher performance. In a sense, in NK models the landscape can be characterised as a mapping of the set of attributes onto performance values.

The components, and therefore the attributes of configuration may be interdependent. They are interdependent if the value of each of the N individual attributes depends on both the state of that attribute itself and the states of K other attributes. As K increases, the interdependencies increase, with K=N–1 being the case of full interdependence among all attributes.

The number of interdependencies given by K characterises the surface of the fitness landscape. For the higher values of K, the performance variation among neighbouring configurations, which differ only in a single attribute, becomes more noticeable (Kauffman 1993; Rivkin, 2000). That means that the higher the K, the more the number of local peaks and the more rugged the landscape.

The K parameter of the model serves as an indicator of the complexity of the problem (Simon, 1962; Page, 1996; Levinthal, 1997). The higher the K, the more complex the problem and the more rugged the performance landscape.

2.9.2. Search and Search Agents in NK Model

The second key feature of the NK model includes an agent(s) searching on fitness landscapes. The agent(s) is controlled by defining its search behaviour – by setting the rules on how to perform the search through the landscape. The original model assumes that the agent searching the landscape does this using trial-and-error, in which one component is mutated at random. If after the mutation the agent finds the new configuration has a better fit, the agents move to the position, which corresponds to this configuration; otherwise, it retains its previous position and mutates another randomly selected component. This implies that the performance or fitness implications of each attribute are assumed unknown to the agents.

Hence, agents must actively 'try out' configurations of attributes and check the result. In an ideal world, a search can continue until no better fitness values can be found by mutating one component. The strategy for evaluating all possible combinations is known as global trial-and-error or exhaustive search. However, in real-world problems search is non-exhaustive, since due to limitations of time, budget and [human intelligence] the number of possible configurations far outweighs the possible number of trials (Rivkin, 2000). This is in line with Simons's (1996) notion of satisficing:

"In the face of real-world complexity, the business firm turns to procedures that find good answers to questions whose best answers are unknowable. Because real-world optimisation, with or without computers is impossible, the real economic actor is in fact a satisficer, a person who accepts 'good enough' alternatives, not because less is preferred but because there is no choice."

For this reason, agents rely on heuristic procedures to find good enough solutions in an acceptable time. Selection then plays a key role in finding the solution to a problem.

Scholars have acknowledged that although biological analogies provide powerful heuristics that can be transferred to studying evolutionary change in other contexts, important differences exist between the evolution of human-made systems and organisms. Therefore, any transfer of ideas and models should be done carefully (De Bresson, 1987; Nelson, 2000; Frenken, 2006). Frenken (2006) highlights a key difference: while organisms evolve through myopic random mutations in single genes, human search is inherently non-myopic.

2.10. Summary

The starting point for this thesis was to establish an understanding of the design process and lay the foundation for analysis of this thesis by reviewing definitions, models and theories of design.

A diverse range of definitions of design was reviewed and a definition was given, as below, to define the focus of work in this thesis:

"Creation of solutions to problems which are functional and aesthetically pleasing".

Holistic design was then defined to view the design solution as an interconnected and integrated whole, where its overall performance arises from nontrivial and complex interactions among multiple parameters and components. This perspective is characterised by the inability to express the overall design performance through a simple mathematical function, the non-independence of individual component performance, and the subjective and emotive nature of user preference.

Different models of design were reviewed, and it was concluded that although the complexities of the solution development phase of the design process are reflected in many of the models, *fewer of them put an emphasis on the complexities of the problem definition stage* and the exploration needed for this purpose.

Several design theories were also reviewed, describing the design as a problem-solving, decision-making or reflective and contextual practice. Several criticisms of these theories were discussed, arguing that the assumption of the existence of topological spaces prior to design is not a valid statement on many design scenarios; hence, such theories are not adequate to cover distinctive aspects of the design process including the generation of new objects and new knowledge. In addition, it was noted that these theories leave small scope for social interactions, which is a key element of design processes, as well as creativity.

The concept of search in different literature domains was reviewed, including human cognitive search and search in design. It was discussed that heuristics, schema activation, bounded rationality, satisficing, abstraction, and representations are key elements of the human search process.

Different search strategies stated in the literature were reviewed. It was noted that although numerous strategies are referred to as "search" or "exploration" strategies in the literature, in effect searching is done through two fundamental approaches of trial-error learning and selectionism. It was argued that other strategies identified in the literature, e.g., existing solutions or causal relationships are mainly to narrow down the search space or decide on the search starting point.

It was also mentioned that the term "search" seems not to be very appealing to the design community and was noted that the unwillingness seems to be mainly related to the

way the term is perceived in the design community. A definition of search as below was given to be used for the purposes of this thesis:

A cognitive, human problem-solving process, under incomplete information where no method of full analysis or guaranteed convergence is available.

After analysing the reviews, it becomes evident that there exists a unanimous consensus among scholars: design inherently involves some form of human search. All theories and models of design also seem to acknowledge that the design process involves a serial and parallel search to explore existing solution landscapes. What seems to be an area of lack of consensus, as well as much academic debate, is whether the activities related to creativity, the creation of knowledge, and social interactions can be interpreted from a search perspective. In addition, the importance of search in problem definition also seems to be undermined in the literature.

Therefore, to this end, as depicted in Figure 2-28, this thesis has addressed the first two research objectives related to the primary question: 'How can we define and characterize design as a search process?' By employing a search theory lens and analysing empirical data from multiple studies, the subsequent sections will fulfil the remaining objectives of this research.

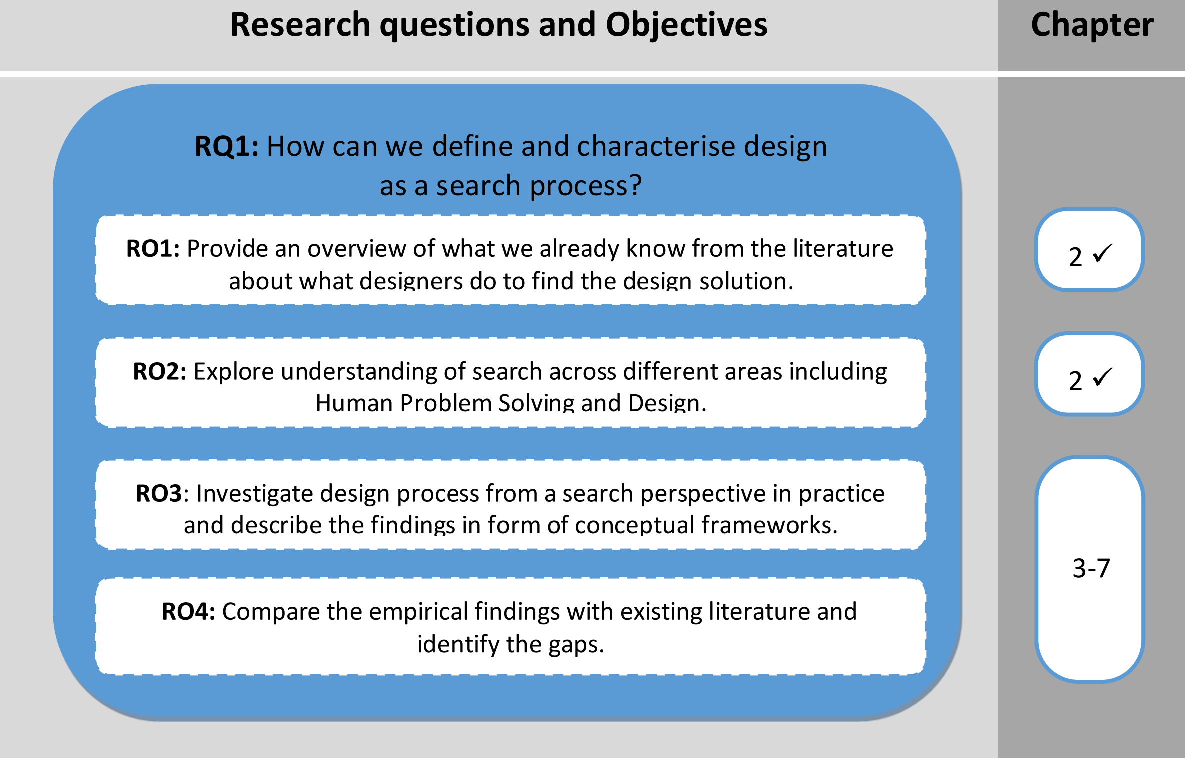

Figure 2-28 Research question 1 and subsequent objectives

3. Methodology and Methods

The purpose of this thesis is to investigate and characterise the ‘search’ process involved in solving ‘holistic’ design problems. More specifically, it aims to understand how the complexity of a product influences the approaches that designers take to search for and reach a design solution. Consequently, the research will be empirical, exploring the processes employed by designers.

The design community advocates the application of certain approaches in conducting design research. Design Research Methodology (DRM) presented by Blessing and Chakrabarti (2009) is perhaps the most widely referenced approach, at least in engineering design research in recent years. This approach is based on structuring the research plan into the four stages of research clarification, descriptive study I, prescriptive study, and descriptive study II.

In this chapter, I will begin by providing a review of the research approach to assess its suitability in guiding this study. The review will be critical due to the interdisciplinary nature of this research. Subsequently, I will discuss other research methodologies, methods, and principles that guided the conduct of this study.

3.1. A Review of Design Research Methodology (DRM)

The ‘DRM methodology’ was initially developed by Blessing, Chakrabarti and Wallace and published in Blessing et al. (1992). The model has evolved through its application in design research and feedback analysis leading up to the comprehensive 2009 textbook by Blessing and Chakrabarti, summarising its methodology, methods, and guidelines.

Because of its continuous application in conducting design research and analysing the received feedback, DRM has gone through continuous improvements. The extended versions together with examples of real project applications are presented in Blessing et al (1995), Blessing and Chakrabarti (2002) and finally in Blessing and Chakrabarti (2009), a textbook which summarises “the DRM methodology and associated methods and guidelines in its entirety”.

The DRM approach structures research into four main stages—research clarification, descriptive study I, prescriptive study, and descriptive study II. It features a

dynamic framework as illustrated in Figure 3-1 (Blessing and Chakrabarti, 2009) that outlines each stage's methods and expected deliverables, emphasising clear output definitions and success metrics.

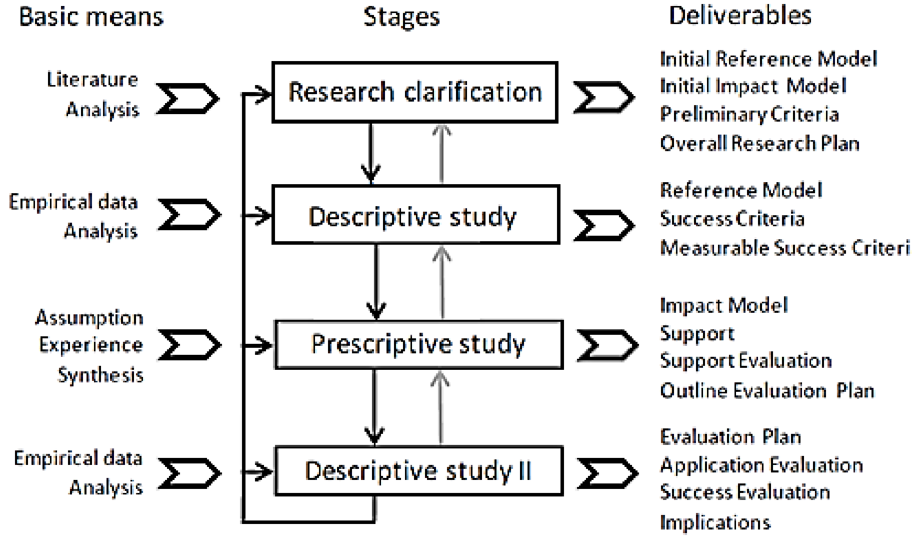

Figure 3-1 The DRM framework: stages, basic means and deliverables (Blessing and Chakrabarti, 2009)

This model is iterative, with possibilities for stages to overlap or be revisited, incorporating both inductive and deductive reasoning as depicted in Figure 3-2. Specifically, it shows how earlier stages can inform later ones, and vice versa, with an inductive approach predominating in the early stages to generate theories or tools, and a deductive method applied in the final stage to test these outputs in real-world scenarios.

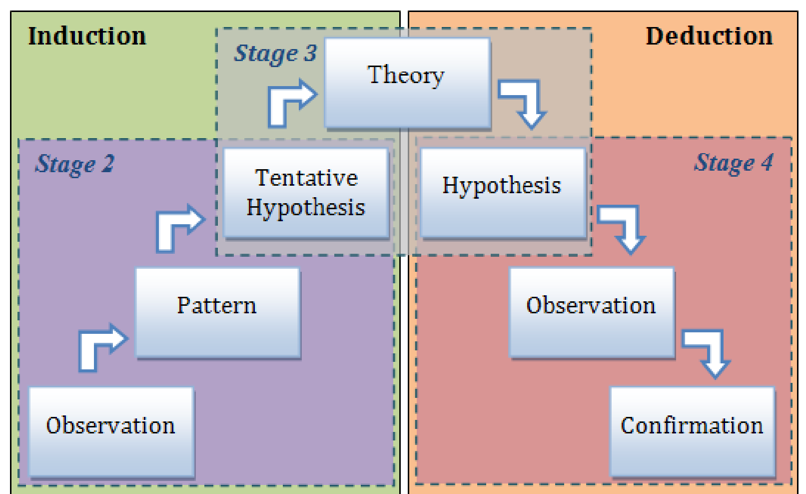

Figure 3-2 the relationship between inductive and deductive reasoning and DRM

Blessing and needabarti (2009) state that it should not be assumed that each of these stages needs to be executed in equal depth in every project. In fact, the degree to which each stage is examined and how the stages inform one another can vary depending on the nature of the project, the state-of-the-art associated with a particular stage and the availability of resources. They propose seven variations of the DRM methodology to suit the particular requirements and constraints of a particular project (Table 3-1).

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

Table 3-1 Variations within four DRM stages (Blessing and Chakrabarti, 2009)

Although design researchers may not explicitly recognize it, all research is fundamentally based on theory in one way or another. The initial stages of conducting empirical research involve articulating the theoretical basis for the study, which includes determining whether the problem under investigation is about building new theory or verifying existing theory.

It can be argued that in the absence of a well-developed theory (or a practical tool, in terms of applied research), the second stage of the Design Research Methodology (DRM) must be conducted comprehensively to lay the foundation for a new theory or tool, or to expand upon an existing theory. Conversely, when a well-established theory exists, this stage may primarily involve a review of the literature.

Therefore, it can be concluded that when the first descriptive study in DRM is carried out with the aim of building theoretical foundations for the research, the approach is comparable to what is conventionally known as grounded theory research. This method

will be discussed further in this chapter. Grounded theory research, which systematically generates theories from meticulously collected and analysed data, mirrors the DRM's focus on developing theoretical underpinnings from empirical observations. This comparison is useful for understanding how DRM accommodates both the construction and the testing of theories, positioning itself within a broader spectrum of research methodologies.

3.2. Grounded Theory

The grounded theory was first introduced by Glaser & Strauss (1967) in the field of sociology, but since then has been further developed and applied in a variety of settings, including design research. It emphasises developing new theories from empirical data rather than testing existing ones. This method emerged as a shift from traditional deductive approaches, which start with a theory and test hypotheses, to a more inductive approach focused on theory building. Grounded theory suggests that the empirical world holds untapped data ripe for discovery and analysis, encouraging researchers to generate new insights through observation (Gregory, 2011).

The key feature of grounded theory is its emphasis on the emergence of the theory from the collected data through a process of discovering concepts and categories, describing the core categories and the relationships between them.

Grounded theory emphasises systematic data collection and analysis methods (Mackenzie and Knipe, 2006). It begins with purposive sampling to select cases rich in information, optimizing resource use and focusing on subjects with relevant knowledge (Patton, 2002). This is followed by theoretical sampling, a dynamic process where data collection, coding, and analysis guide subsequent data gathering, aiming to refine and develop the emerging theory (Glaser and Strauss, 1967). Strauss and Corbin (1998) highlight this approach's ability to uncover variations and enrich conceptual categories. Sampling continues until theoretical saturation—the point where no new data alter the category's properties—is achieved (Chun Tie, 2019). Saturation ensures category robustness through diverse data (Glaser and Strauss, 1967) and serves as a qualitative research benchmark for sampling size. However, Guest *et al.* (2006) caution that while

saturation is conceptually valuable, it offers limited practical advice for determining sample sizes before data collection.

In grounded theory, data collection often involves interviews and observations, leading to initial analyses that form preliminary interpretations, categories, and theories. These initial findings guide further data collection to refine, validate, or challenge emerging concepts (Strauss & Corbin, 1998). This iterative process, involving constant comparison and in-depth analysis, allows researchers to develop theories grounded in the data, starting without significant preconceptions. However, as research progresses and saturation is reached—where new cases no longer provide additional insights—the benefits of adding more data decrease (Khurana and Rosenthal, 1998). Grounded theory is particularly effective in areas lacking established theories or where understanding the processes of meaning construction from shared experiences is critical (Greenwood, 2006). The focus is on generating theoretical contributions to the study field, emphasizing the significance of the results over the methodology.

3.3. Design Research Methodologies Vs Grounded Theory

Several studies have compared design research methodologies with grounded theory, including works by Goldkuhl (2004), Holmström *et al.* (2009), and Gregory (2011). Goldkuhl (2004) particularly outlines the integration of grounded theory techniques into design science research to enhance grounded practical knowledge. He proposes three grounding types to improve design science research: internal, empirical, and theoretical. Empirical grounding evaluates the effectiveness of knowledge application, while external theoretical grounding connects this action knowledge to broader theoretical insights, including general explanatory theories. Internal grounding investigates the intrinsic values, categories, and coherence of the knowledge base.

Another study by Holmström *et al.* (2009) compares these two research strategies and concludes that they complement each other. They consider design science to be exploratory in nature and contrast it with conventional Operations Management research, which often seeks to explain empirical phenomena and is therefore known as explanatory research (Table 3-2 and Table 3-3)

Table 1: Exploratory and explanatory research

	Exploratory Research (Design Science)	Explanatory Research (Theoretical Science)
The phenomenon	"artificial phenomena" have to be created by the researcher	"out there"
Data	created, collected, and analyzed	collected and analyzed
End product	solving of a problem	explanatory theory, prediction
Knowledge interest	pragmatic	cognitive/theoretical
Disciplinary basis	engineering, fundamentally multidisciplinary	natural and social science, primarily unidisciplinary

Table 3-2: Exploratory and explanatory research (Holmström et al., 2009)

Research Type	Exploration (Design Science)		Explanation (Theoretical Science)	
Research Phase	1. Solution Incubation	2. Solution Refinement	3. Explanation I	4. Explanation II
Objective	Development of an initial solution design	Refinement of the initial solution design; solve the problem	Development of substantive theory; establish theoretical relevance	Development of formal theory; strengthen theoretical and statistical generalizability
Means	• Identification of interesting goals, situations, and possible solutions • Scanning of parallel knowledge domains • Abductive cross-disciplinary reasoning	• Implementation of solution designs • Confirmation of intended consequences • Cooptation of unintended consequences • Iteration between solution designs, implementation and evaluation • Inductive and deductive reasoning	• Theoretical reflection of the refined solution design • Linking the solution design to a research program and theoretical discourse • Inductive and deductive reasoning; hypothesis building	• Theoretical and empirical examination of relevant contingencies • Development of formal representations of the solution design • Implementation and refinement of the solution design in multiple contexts • Inductive and deductive reasoning; hypothesis building and testing
Knowledge interest and research approach	• Pragmatic • Action research • Subjective	• Pragmatic • Action research • Subjective and intersubjective	• Cognitive/Pragmatic • Evaluative research • Intersubjective	• Cognitive • Evaluative research • Intersubjective
Examples	• Trovinger and Bohn (2005)	• Greasley (2005)	• Mid-range theories of the focused factory (Ketokivi & Jokinen, 2006) and flexibility (Upton, 1997)	• Transaction-cost theory (Williamson, 1996) • Structural contingency theory (Donaldson, 2001)

Table 3-3 Exploratory and explanatory research elaborated: Bridging Practice and Theory (Holmström et al.,2009)

Gregory (2011) conducted a systematic comparison of characteristics of design science research (used in Information System design) and the grounded theory to identify the commonalities, differences and possible complementary uses of the two research strategies. Table 3-4 provides an overview and comparison of the characteristics of design science research and the grounded theory method.

Identified Category Design	Design Science Research (DSR)	Grounded Theory Method (GTM)
Theory focus	DSR-1: The primary focus in a design science research project is mostly given to the design research part (i.e., the creation of an IT artefact), as opposed to the design science part (i.e. generating new knowledge).	GTM-1: The focus of the grounded theory method is the discovery of grounded theory (i.e., categories and relationships between them).
Research process	DSR-2: The design science research process involves the search for a relevant problem, the design and construction of an IT artefact, and its ex-ante and ex-post evaluation.	GTM-2: The grounded theory research process involves theoretical sampling and constant comparisons to develop grounded theory and make a substantial theoretical contribution.
Research goal	DSR-3: An important goal in design science research is to search and solve practically relevant real-world problems (or classes of problems).	GTM-3: An important goal in grounded theory research is to produce a theory that fits with the real world and is grounded in empirical data.
Nature of research	DSR-4: Design science research is a general research approach with a set of defining characteristics and can be used in combination with different research methods.	GTM-4: Grounded theory is an evolving research method with sets of guidelines, principles, and techniques.
Epistemology	DSR-5: Design science research is conducted most frequently within a positivistic epistemological perspective.	GTM-5: Grounded theory method is conducted most frequently within an interpretive epistemological perspective.
Research outcome	DSR-6: The outcome of design science research (i.e., the problem solution) is mostly an individual or local solution and the results cannot be readily generalized to other settings	GTM-6: The outcome of applying the grounded theory method is mostly a substantive theory in the domain of study and on its basis; it is possible to further develop formal theory.

Table 3-4 Comparison of characteristics of design science research and grounded theory method (Gregory, 2011)

They conclude that there exist opportunities for researchers to blend the two strategies and leverage the advantages of both, and in doing so combine “the goals of solving a real-world problem to achieve practical relevance and developing theoretical

contribution to achieve scientific rigour". However, they warn that in using such a pluralistic research approach the researcher must take great care in combining the different research strategies in a way that is consistent with the characteristics of every single strategy.

3.4. Justification of Employed Methodology

This research aligns with the Design Research Methodology (DRM), particularly as outlined in Table 3-1, line 2. Yet, due to the absence of a comprehensive theory for predicting holistic design search processes, grounded theory's guidelines and techniques are also beneficial. DRM offers a broad framework but lacks detailed guidance on sampling and data analysis, making it insufficient alone for this study. Grounded theory facilitates a theory-building approach, identifying key elements of holistic design search. However, the challenges of achieving saturation within the constraints of a PhD study—due to complexity, uncertainty, and limited resources—necessitated a pragmatic approach. This approach involved using theoretical sampling for decision-making on sampling strategy while adhering to DRM for overall research execution.

The study would be exploratory in nature, in order to provide rich insights into the design process for holistic designs that cannot easily be decomposed. Due to the nature of the study, a case study approach is used which is conducted through in-depth interviews with designers. The subsequent sections will address the challenges and limitations encountered with case studies as the chosen method and interviews as the primary tool for data collection.

3.5. Case Study, Challenges and Limitations

Building theory from case studies is a common research strategy that includes using one or numerous cases to build theoretical propositions and hypotheses, from case-based, empirical evidence (Eisenhardt, 1989).

A single-case study can provide a detailed understanding of a phenomenon (Siggelkow, 2007), but multiple-case studies contribute more effectively to theory development, as they ensure the theory is well-supported, accurate, and broadly applicable (Yin, 1994). Eisenhardt and Graebner (2007) note a trade-off between the

depth of insight from single-case studies and the theoretical robustness achieved through multiple cases. Comparing multiple cases helps ascertain whether findings are unique to a single instance or consistently observable, thereby strengthening the theory with varied empirical evidence. This approach clarifies constructs and their relationships by allowing for more precise definitions and appropriate construct abstraction (Eisenhardt and Graebner, 2007). Nonetheless, balancing theoretical depth with empirical richness remains a challenge, especially in meeting expectations for the detailed narratives characteristic of single-case studies (Eisenhardt and Graebner, 2007).

Although multiple cases are likely to result in a more robust theory, sampling becomes more complex. Building theories from case studies relies on theoretical (as opposed to statistical) sampling. This approach involves selecting cases that significantly illuminate and extend the relationships and logic among constructs (Eisenhardt and Graebner, 2007). Cases are chosen based on their potential to contribute to theory development through methods such as replication, theory extension, contrary replication, and the elimination of alternative explanations (Yin, 1994).

A major reason for the popularity and applicability of case studies in theory building is that it is one of the best research strategies (and arguably the best) for bridging from rich qualitative evidence to deductive research. "Its emphasis on developing constructs, measures, and testable theoretical propositions makes inductive case research consistent with the emphasis on testable theory within mainstream deductive research. In fact, inductive and deductive logics are mirrors of one another, with inductive theory building from cases producing new theory from data and deductive theory testing completing the cycle by using data to test theory" (Eisenhardt and Graebner, 2007).

In case studies, each case functions as a separate experiment and an independent analytical unit. Similar to related lab experiments, multiple cases act as replications, contrasts, and extensions of the evolving theory (Yin, 1994, cited in Eisenhardt and Graebner, 2007).

Meredith (1998) highlights three main advantages of case studies identified by Bebensat *et al.* (1987), which justify the selection of this approach for this research: (1) They enable the study of phenomena in their natural environments, fostering the generation of relevant theories through the observation of real practices. (2) Case

studies facilitate comprehensive answers to 'why,' 'what,' and 'how' questions, offering deep insights into the phenomenon's full complexity. (3) They are particularly suited for preliminary exploratory research, where the variables and the nature of the phenomenon are not yet clearly defined.

Case selection is a major challenge of the case study approach. There are two aspects to this challenge: the number of cases and the sampling strategy. The DRM methodology offers no specific advice on these issues. Grounded Theory, however, involves specific rules for developing theory out of data, that is, for moving from description to the theory. Regarding sampling strategy, the approach emphasises theoretical sampling. Strauss and Corbin (1998) described theoretical sampling as a means to "maximise opportunities to discover variations among concepts and to densify categories in terms of their properties and dimensions". Likewise, Charmaz (2006) has defined theoretical sampling as a means of focusing on data collection and increasing the analytic abstraction of theory by illuminating variation and identifying gaps that require elaboration.

As discussed earlier, the theoretical sampling method from grounded theory is deemed most suitable for this research, though uncertainties around data saturation have limited its full adoption. An alternative, polar types sampling, is recommended for scenarios with fewer cases due to constraints like time(Eisenhardt and Graebner, 2007). This method involves selecting extreme cases (e.g., very high and very low performers) to highlight contrasting patterns more clearly fitting for PhD research with limited resources. It's crucial to choose cases where the phenomenon is clearly observable, such as critical, extreme, or revelatory cases (Pettigrew, 1988, cited in Eisenhardt, 1989), acknowledging the subjectivity inherent in non-random sampling.

A key consideration for conducting this research has been selecting the units of analysis in a way to cover different groups to maximize the similarities and differences of information. This led to studying three distinct industries: Graphic Design, Small Household Appliance Design and Automotive Design. Building on the sampling approach discussed, the selection of sectors for the case studies of this thesis, was strategic to explore the spectrum of complexity in holistic design. Graphic design represents a relatively less complex domain, where the design elements are more contained and the

design process is more linear. This contrast with the automotive sector, which epitomises high complexity due to its multifaceted engineering requirements, consumer expectations, safety regulations, etc., and providing a rich context for analysing intricate design processes. Small domestic appliances fall in the intermediate complexity range, bridging the gap between graphic design and automotive. This sector offers insights into the challenges and considerations when designing products that are both functional and aesthetically pleasing, yet less complex than automobiles. This gradation of complexity across sectors allows for a detailed understanding of how complexity influences holistic design processes, thereby aligning with the research's aim to examine the role of complexity in holistic design.

Further details about the companies selected for study within each case are provided in the respective chapter dedicated to each case study.

3.6. Data Collection Methodology

The progression to data collection involved choosing suitable methods, often qualitative for case studies to deeply understand the interplay between phenomena and their contexts. Iacono *et al.* (2011) highlight the significance of selecting pertinent variables for study, beyond just case selection. Given the range of possible data sources including interviews, archival data, and observations (Eisenhardt and Graebner, 2007), this research employed a multifaceted data collection strategy, primarily focused on semi-structured interviews complemented by secondary data from prior interviews with designers and subject matter experts. Grounded in theoretical sampling, as emphasised by Strauss and Corbin (1998) and Charmaz (2006), this approach aimed to uncover variations and identify gaps across different domains, thus ensuring a rich theoretical development.

According to Fontana and Frey (2005), based on the degree of structuring, interviews can be categorised into three: structured interviews, semi-structured interviews, and unstructured interviews. Structured interviews involve a predefined set of questions, minimizing the influence of the interviewer. Unstructured interviews, lacking a pre-set framework, rely on spontaneous question generation based on interviewee responses, potentially leading to varied data patterns. Semi-structured

interviews blend these approaches, mixing structured questions with the flexibility to explore unforeseen topics, advantageous for discussing unexpected issues.

The semi-structured approach employed in this research reflects the fact that no developed theory exists that explains how designers approach unstructured holistic problems, where established decomposition methods do not work. For example, it is not possible to decompose the aesthetic performance of the car into independent performance requirements for interior, exterior and trimming design. This method allowed for adaptability in probing the design process, critical for understanding complex design challenges. Using a semi-structured interview gives the interviewer more freedom to guide the interview and meantime enables the interviewees to expand on what they think to be important.

At the outset of the study, an interview schedule was developed and subsequently pilot-tested with an ex-design engineer from a leading automotive company. During the data collection phase, this engineer was affiliated with the University of Cambridge Engineering Design Centre (EDC), offering a valuable chance to refine the interview schedule further. The objective extended beyond ensuring the schedule's suitability and comprehensiveness; it was crucial to frame questions flexibly, allowing for elaboration as needed and ensuring their clarity for interviewees. This preparatory phase was pivotal in customising the semi-structured interviews that ensued. The updated interview schedule informed the conduct of semi-structured interviews across different cases throughout 2013 and 2014.

The case studies primarily consisted of interviews with designers, engineers, or directors, who provided valuable insights into their design processes. Below is a brief overview of the participants, while detailed information about the selected companies, their operations, and the interviewees will be covered in later chapters specific to each case study.

- Graphic Design: Interviews were conducted with three principal designers, who also served as directors, from three graphic design agencies. These cases highlighted the comprehensive design process from client engagement to final product delivery.

- Automotive Design: Alongside the pilot study participant, who shared insights from his experience in the automotive industry, three design engineers from various departments of a pioneering automotive firm offered perspectives on the complexity inherent in car design, underscoring the collaborative nature of automotive design and engineering.
- Small Household Appliance Design: Two interviews were conducted at design consultancies specialising in small domestic appliances serving to explore the complexity spectrum lying between graphic design and automotive. In one interview, a designer was present, while the other involved both a designer and an engineering lead. These discussions provided insights into how technical requirements and design aesthetics are integrated.

Following the initial interviews, two additional open-ended interviews were conducted with two participants from the automotive companies, including one from the pilot study. In total, the research comprised 11 interviews (including the pilot study) involving 9 respondents, with two being interviewed twice. Each session lasted approximately 90 minutes, predominantly held at the participants' workplaces. This setting enabled the interviewees to access and reference design materials and examples as necessary. All interviews were recorded and subsequently transcribed. Table 3-5 provides an overview of the participants, outlining their roles and sectors.

Referred to as	Role	Sector
graphic designer A	Director/Designer	Graphic design
graphic designer B	Director/Designer	Graphic design
graphic designer C	Creative director	Graphic design
creative director, design consultancy A	Creative director	Design consultancy
product engineer, design consultancy B	Consultant Mechanical Engineer	Design consultancy
design engineer, design consultancy B	Senior Mechanical Engineer	Design consultancy
ergonomics supervisor, pilot study	Ex- Human Factors and Ergonomics Supervisor	Automotive
DET coordinator, automotive firm	DET coordinator Design Enabling Technologies coordinator	Automotive

Referred to as	Role	Sector
HMI specialist, automotive firm	Human Machine Interface specialist in the Advanced Engineering team	Automotive
infotainment specialist, automotive firm	Human Machin Interface specialist the Infotainment team	Automotive

Table 3-5 Case study participants' overview

Beyond access considerations, participant selection was primarily based on their ability to provide deep insights into the design process within the contexts of the cases studied, showcasing a spectrum of complexities. This approach allowed for an in-depth exploration of design solutions with varying degrees of complexity in real-world settings. However, it's important to note that this approach might not capture the full spectrum of practices across all design domains, potentially limiting the generalizability of the findings or missing aspects not explored in the interviews. To address a gap in stylistic perspectives from the automotive industry, the research was supplemented with secondary data from interviews with exterior and interior designers published in Motor Trades Insight Magazine Online. This secondary data was further validated by one of the primary interviewees.

Moreover, the nature of semi-structured interviews introduces another limitation. The effectiveness of this method significantly depends on the interviewer's skills and the interviewees' willingness to share information, which might impact the depth and breadth of the data collected.

Using interviews in case studies, while providing valuable insights, requires delicate trade-offs between depth of understanding and breadth of coverage in research design. By strategically selecting participants and incorporating secondary data, this study has aimed to address these limitations.

3.7. Research Ethics and Informed Consent

When conducting case studies that involve semi-structured interviews, several ethical considerations are paramount to ensure the research is carried out responsibly and respectfully. Creswell (2014) highlights the critical importance of obtaining informed consent, maintaining confidentiality, minimizing harm, respecting participants, and

securing ethical approval from relevant institutions. These principles were adhered to throughout this research process, as detailed below:

Prior to the interviews, participants were contacted via email to introduce the research's aims and the nature of their involvement. This initial contact provided a broad overview of the interview's intent, ensuring participants were aware that the information collected would be used anonymously in the thesis. This step was crucial for setting the groundwork for informed consent, aligning with Creswell's advocacy for transparency and participant understanding in research engagements.

Informed Consent Process**:** Further detailed verbal information about the study was provided to participants at the outset of each interview, reinforcing the initial email communication. This included an explanation of the study's purpose, the voluntary nature of their participation, the procedures involved, and their rights to withdraw at any time. This process ensured that consent was fully informed and documented, respecting participants' autonomy as advised by Creswell (2014).

Confidentiality and Anonymity**:** To protect participant privacy and adhere to ethical standards, all data collected were treated with confidentiality. Names and identifying details were anonymised in the thesis and any publications arising from this research, safeguarding against potential harm or discomfort.

Participant Engagement and Ethical Considerations**:** Participants were assured of their right to review the interview transcripts, offering them the opportunity to correct or clarify their statements. This practice not only ensured the accuracy of the data but also empowered participants, reflecting a respectful and collaborative research approach.

These ethical practices have been instrumental in establishing a trustworthy and respectful relationship between the researcher and participants, contributing to the richness and depth of the insights gained.

3.8. Data Analysis Methodology

Qualitative data analysis can be viewed as the process of making sense of research participants' views and perspectives (Cohen *et al.,* 2007), or as described by Gibbs (2007)

is the process of transformation of collecting qualitative data, done through analytic procedures, into a clear, understandable, insightful, trustworthy and even original analysis. Green *et al.* (2007) also describe qualitative data analysis as “a systematic and essentially taxonomic process of sorting and classifying the data that have been collected”.

The literature presents varieties of qualitative data analysis approaches and as discussed by Punch (2005) “this variety and diversity in approaches underline the point that there is no single right way to do qualitative data analysis -no single methodological framework. Much depends on the purposes of the research, and it is important that the proposed method of analysis is carefully considered in planning the research and is integrated from the start with other parts of the research, rather than being an afterthought”. Nieuwenhuis (2007) notes that “qualitative data analysis tends to be an ongoing and iterative process, implying that data collection, processing, analysis and reporting are intertwined, and not necessarily a successive process”.

Despite the variety of approaches, it is possible to identify commonalities between them. In their book “Qualitative Data Analysis: An Expanded Sourcebook” Miles and Huberman (1994) discuss a 'fairly classic set' of six moves common across different types of analysis:

1. Giving labels to the initial set of data obtained from observation, interviews and documentary analysis; means high-level coding of the data as an example of particular things, which might be of interest.
2. Adding comments and reflections (commonly referred to as memos).
3. Going through the materials trying to identify similar phrases, patterns, themes, relationships, sequences and differences between sub-groups and so on.
4. Using the identified patterns and themes to help focusing on further data collection.
5. Gradually elaborating a small set of generalisations that cover the consistency one discerned in the data.

6. Linking the generalisations to a formalized body of knowledge in the form of constructs (sets of concepts or ideas) or theories.

Green *et al.* (2007) identify four steps of analysis in high-quality papers: immersion in the data, coding, creating categories, and the identification of themes.

The grounded theory approach also has guidance for data analysis, which is mainly linked to its sampling strategy. The approach is based on the constant comparative method in the sense that observations from the previous stage of data analysis are compared to the next stage and this is carried out until the point of 'theoretical saturation'.

The main purpose of the data analysis of this thesis has been to provide a detailed picture of the design process and its characteristics from a 'search' viewpoint. So, in the first place, the collected data are expected to provide the foundation for the development of a conceptual framework or frameworks that describe design from a search perspective. In light of this and considering the time and resource limitations of this study, the three-stage thematic data analysis process as suggested by Miles and Huberman (1994) was considered the most practical method of data analysis and interpretation for this research. This bottom-up approach enables seeking any emergent patterns and themes from the interviews with the participants. The approach has three main components of Data reduction, Data display and drawing and verifying conclusions as depicted in Figure 3-3.

Data reduction is an analysis that helps sort, focus, discard, and organise data in a way that allows conclusions to be drawn and verified. In the early stages, it happens through editing, segmenting, and summarising the data. In the middle stages, it happens through coding and memoing, and activities like finding themes and patterns. In the later stages, it happens through conceptualising and explaining, since developing abstract concepts is also a way of reducing the data. Data reduction occurs continually throughout the analysis, and the objective should be to reduce the data without significant loss of information. Data reduction and coding have been done through using OneNote which enables categorising content into different sections and subsections, attaching notes and labels and interlinking them.

Data display takes the reduced data and displays it in an organised, compressed way so that conclusions can be more easily drawn. Miles and Huberman (1994) suggest that careful data display is an important element of data reduction and the selection and suggest that better displays are a major avenue to valid qualitative analysis. There are many different ways of displaying data like tables, charts or diagrams. This research will use tables as a medium for displaying data.

Conclusion drawing and verification are where one decides what things mean by noting regularities, patterns (differences/similarities), explanations, possible configurations, causal flows, and propositions. While drawing conclusions rationally follows data reduction and data display, in effect it happens more or less concurrently with them. Therefore, possible conclusions may be identified early in the analysis, but they may be imprecise and ill-formed at this stage, but will be sharpened through further analysis (Miles and Huberman (1994), cited in Punch, 2005)

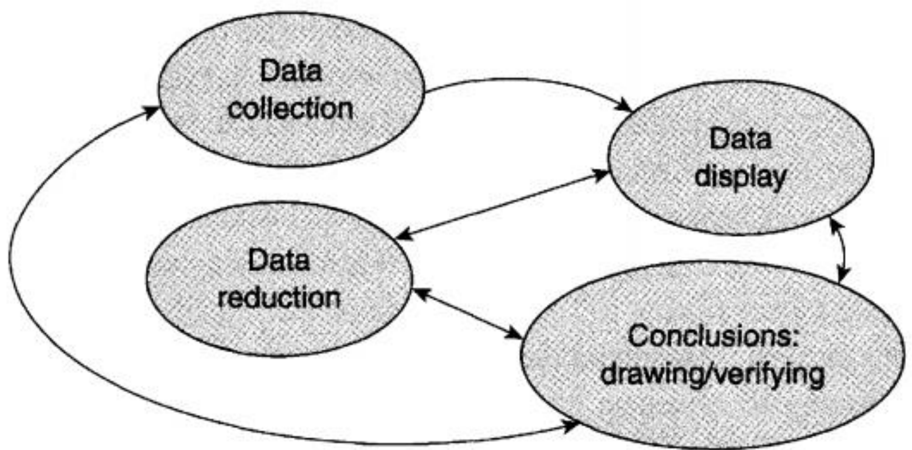

Figure 3-3 Components of data analysis: interactive model (Miles and Huberman, 1994)

Parallel with the approach suggested by Milles and Huberman (1994) attention was made to the process of building theories from case study research, as suggested by Eisenhardt (1989). He describes the process to start with the initial definition of the research question and suggests that this stage includes a priori identification of variables ("constructs") from the extant literature guiding the research process. The second question of this thesis assumes that there are variables that can identify the type of search that designers do. From the literature review, complexity can be the nominated value, but this needs to be concluded and confirmed or rejected by this research.

Eisenhardt (1989) proposes that tentative themes emerging from the data need to be continuously compared and contrasted with the literature. The idea is to iterate toward a theory that truthfully reflects the data. Therefore, there should exist propositions that organise the frame of the study and need to be supported and demonstrated by evidence from cases by empirical evidence. He adds, "since it is generally not realistic to support every theoretical proposition with every case within a text itself, the use of extensive tables and other visual devices that summarise the related case evidence is central to signalling the depth and detail of empirical grounding. In other words, the use of summary tables and aids that summarise the case evidence complements the selective story descriptions of the text and further emphasizes the rigour and depth of the empirical grounding of the theory". "These "construct tables" summarise the case evidence and indicate how the focal construct is "measured," thus increasing the "testability" of the theory and creating a particularly strong bridge from the qualitative evidence to theory-testing research". Parallel to this, Voss *et al.* (2002) suggest that in theory-building research, no matter how inductive the approach is, the researcher needs to have a prior view of the categories or general constructs they intend to study, and their relationships. As per Miles and Huberman (1994), this can be done through the construction of a conceptual framework that underlies the research, which can help the researcher "to think carefully and selectively about the constructs and variables to be included in the study".

In line with the above, the data analysis of this thesis utilises and relies extensively on the use of tables and frameworks summarising the case evidence and signalling the empirical grounding of conclusions made, as discussed in the subsequent chapters.

3.9. Summary

This thesis examines how designers approach holistic design problems. Design Research Methodology (DRM) and Grounded Theory were reviewed, compared, and contrasted to clarify which methodology would be the most suitable approach for conducting this research. It was mentioned that each of these methodologies has its own strengths and limitations and as such while for the general guidance of this research, DRM has proved to be an insightful framework, it was insufficient to guide the strategies for the data

collection and analysis. Hence, instructions on purposeful sampling from the grounded theory approach were pragmatically adapted to guide the sampling process. Specifically, polar sampling was taken on, which enabled the researcher to observe comparable and contrasting patterns in a limited time. It is also clear from the arguments in this chapter that the research questions at the heart of this enquiry needed to be answered primarily through a qualitative approach. Hence, a case study approach using semi-structured interviews was identified to be the most appropriate design to use in pursuing the research questions in this thesis. Finally, it was noted that for the purpose of data analysis, the three-stage thematic data analysis process as suggested by Miles and Huberman (1994) was an appropriate approach, and as such was pragmatically employed for the process of data analysis and interpretation in this thesis.

4. Case Study 1: Graphic Design

Study one included interviewing designers from three graphic design agencies. Graphic design includes a wide range of disciplines including “illustration, typography, photography, layout, packaging design, book design, newspaper and magazine design, corporate design and website design” (Meggs, 1992). What is core in all these disciplines is the communicative objective of design and the designer's intention to produce artefacts that are illustrative, persuasive and informative (Meggs, 1992).

Graphic designers are typically involved in every phase of the design process, from meeting with clients to determine the scope of a project, to the creation of the actual design and presenting it to the client. As part of study one, three designers, who were also the directors of their companies, were interviewed.

The first company defines itself as a “creative agency specialising in business improvement and business idea development through brand, design and digital innovation”. Formed in 1997, the founders’ backgrounds are in graphic design, marketing, and communication.

As per the interviewee, the company develops products that address clients’ needs for either or all the followings:

1. Building recognition and helping the client to stand out in the sector.
2. Helping the client to be more understandable and memorable by people and,
3. Making a product or service desirable.

They work with a wide range of clients from small start-ups and social enterprises to global corporations on different projects including the design of brand manuals, material for marketing campaigns and business promotion, Websites etc.

As part of this study, one of the founders of the company who was also heavily involved in the design process was interviewed. He also had a background in marketing and communication which enabled him to better understand the client’s requirements. Therefore, he was able to provide a very detailed view of the process involved in designing products from start to end, i.e., from the initial discussion with the client about their needs to a final design solution that could address those requirements.

The second company produces branding & marketing collateral for corporates, SMEs and start-ups. More specifically, their services include web, brand and corporate identity design, business-to-business marketing, presentations, advertising, brand development, brochures and multimedia. Again, the director and the founder of the company was interviewed in this case, who was also involved in the design process and had a thorough knowledge of the entire design life cycle.

The third company mainly specialised in print and new media projects for Entertainment & Business. The creative director of the company who has been involved in almost all the existing projects of the company from the very early stages was interviewed.

All three companies appeared to engage in very similar processes, encompassing the following top-level activities:

- Agreeing on the project brief with clients: this is a step where the graphic designer tries to gather as much information as possible about client requirements and expectations. At this stage, the designer works with the client to define objectives. One of the cases required their client to complete a standard questionnaire at this preliminary stage.
- Researching the client's competitive environment: During this stage, the designer would search for information on the competitors, market, trends, target audience, prospects, and point of differentiation. The purpose of this stage is mainly to give the designer "a 360° view of the client's ecosystem and generate ideas that fit the market, industry trends, and the client's customers" (Lewis, 2015).
- Brainstorming on ideas, visualising and sketching.
- Building the design and refining it.

The companies were all small companies, with a very simple structure. In all three cases, it wasn't uncommon at all that a single designer undertakes all the required activities throughout a design project.

The interviews lasted about 100 minutes each and were recorded and later transcribed. The transcription was sent to the interviewees for their comments and approval.

4.1. Search in Graphic Design

In graphic design, diverse elements such as signs, words and pictures are combined in order to communicate a message. Hence, a graphic design product has a dual nature: communicative and visual; it is this communicative function of the graphic space that distinguishes it from other visual arts (Meggs, 1992).

Some graphic designers work with tight briefs, i.e., a statement of the problem or opportunity (e.g., a 'logo' with tightly defined features), in which case the design output may not be holistic; in this case, the design can indeed be decomposed into elements and features. However, two of the three interviewees mentioned that they do not work to tight briefs. They work closely with the client to identify the root causes of their problem and then decide on the format of the solution. Thus, the desired design solution incorporates an emergent set of (mostly qualitative) client desires, which interact in nontrivial ways. Thus, the designs on which our interviews focus are holistic.

4.1.1 The Process of Identifying a Problem Space

The process of understanding the problem, which one of the interviewees called "diagnosis", is a collaborative process that typically involves the identification of and discussion with different stakeholders of a business (including customers, staff and directors) in order to get "an honest perspective" of what the problem might be. One common problem that designers face in this stage is that the people involved in the approval process are not necessarily those involved in the briefing process (graphic designer C, 2013). Therefore, all of the participants mentioned that identification of the key stakeholders and understanding the requirements from their perspective is an essential step at the beginning of the project. The diagnosis stage also includes understanding the competitive environments of the client.

This process leads to re-writing the brief, which then typically includes a description of the overall format of the final solution, but only in the language of the client's desires.

In other words, the rewritten brief proposes what client needs can be met (in the client's language), but not how, i.e., the "technical" (design) solution is still hidden and undefined. The proposed solution might be different from what the client has initially asked for, for example, a customer might request a logo, but after the diagnosis stage, it may be agreed that 'direct mail' can address the problem better. However, the new proposal describes only the problem, a changed set of client needs, not the solution (e.g., the client needs to move from a logo's widely seen visual impression to a widely experienced direct mail contact).

In most cases, before reframing the customer requirements, designers meet among themselves in order to confirm the understanding of the problem and discuss possible ideas, in very broad terms, which might solve the problem. The aim of this process is to help the team to develop a multi-perspective understanding of the problem space and to collaboratively come up with solution ideas. Besides, the team members will be able to exchange external information, as not everyone can attend all appointments with the client. These conversations among the designers (informally) also address feasibility in principle.

In summary, this thesis identified three key activities within the design process: first, the understanding of the problem space through reviewing the competitive environment, engaging in knowledge pooling, and conducting stakeholder and needs analysis; second, the reframing of the problem through collaborative efforts between the client and the design team; and third, the determination of a broad format for the solution.

4.1.2 The Process of Searching the Solution Space

After redefining the problem space, the design team starts thinking about solutions, at first through manifestations of initial general ideas. The actual search for the solution within the already-defined search space starts at this stage. This happens in two broad stages: the first stage produces a broad solution characterization via a creative and then eliminative development of mental models. Then, the much better-defined space of the mental models is searched iteratively with specific "mock-ups" or candidate designs.

Creative generation of mental models

First, the creative phase of developing mental models was explained by one of the interviewees as follows:

> "So, then we are down to kind of expression, and that leads to what the detailed format and shape would be, then we are almost to production. There is a whole process then that kicks in just around production and graphics kicks in at that point. There is a process before the design process; for me, the classic interpretation of the design kicks in at this stage, which is how you pull out all things together to say what the thing will be. And then obviously we need to refine that" (graphic designer A, 2013)

Creativity in design arises largely at this stage when diverse ideas converge, initiating a defining point that facilitates the creation of a coherent and productive solution for the design problem to emerge, which also raises questions about the specific characteristics that trigger these insightful beginnings, or in other words, the "starting points" for searching the solution landscape. Table 4-1 presents the result of thematically analysing the interview data, to delineate general categories of triggers for creative ideas. The first column of the table lists the various categories of these triggers, offering a structured overview of the sources from which designers draw inspiration. The second column, on the other hand, presents concrete examples extracted from the interviews, grounding these categories in real-world instances.

Sources of ideas	Evidence from the interviews
Actual problem and relevant materials designers are supplied with	"we will look at the material we are supplied with, so for example for designing a poster [for a movie] we are normally provided with photographs, sometimes we make a link to a trailer on YouTube, so we see what the film is being sold as…and our poster needs to market and being kept with that" (graphic designer C, 2013)
Competitor designs	"It is very useful to benchmark your client's company against the competitors…, and then at the end, we put our client and we say you are not as good as them in this respect. This is a very easy way to work because if you know where you are deficient and where your competitors are better, you got something to aim for" (graphic designer A, 2013) "But when we researched the competitors, there was one company that had done this idea of people round the table planning, and that is a very

Sources of ideas	Evidence from the interviews
	good message because we wanted to show collaborations" (graphic designer B, 2013)
Successful examples from non-competitors' work	"We might also talk about people who are not their competitors but to the side of their industry, but might be a good reference for us… So, in this job for company M [which is a software manufacturer] we got our inspiration from looking at telecom companies. …we first looked at other software companies, and they are all really doing the same stuff. It is all sorts of boring, specifications of things, which are no good if you wanted to attract people in the exhibition. But when we looked at the Sony Ericson, they were doing some nice things with phones that were to do with this idea of real people and their own background, so there was a sort of cartoons world which was really inspiring" (graphic designer B, 2013)
Trends in the industry and general market trends	"Every day we look at what is going on, what else is being done in the world, we have to stay on trends; we have to stay not only on what is going on in the movie business but also what is going on in advertising generally, with publishing and other things. Certain types of faces may become trendy or certain colour schemes, so you need to know the rules" (graphic designer C, 2013)
Triggers from past experience	"It is because of the past references that you got for graphic, design, so you know what works with what." (graphic designer A, 2013) "What we also have is experience again and if it is the client that we have worked with before, we can all refer to our experience with that client. We say normally they like this thing to be like this, normally they like this process to be followed by that, normally they like the logo to be bigger, normally they like it blue. …But it is the experience that let you know that client won't be happy or is less likely to be happy with that solution" (graphic designer c, 2013)
Combining ideas	"And sometimes you can look at images, and you see a small part of images and say that part will work really well with that, you get the feeling of composition as a whole and you can pull it together in your head" (graphic designer C, 2013)
Inspiration from other sources	"It may be actually something that you have seen on the telly, something that might influence your visual style, also something you thought it was clever, or pretty, and they can come from all walks of life, you may see a nice shoe, and you think that is great I love that colour and that colour makes me think of storms. And if I am working on jobs that need storms then maybe I will look at the way of trying to get that colour in" (graphic designer C, 2013)

Table 4-1 Sources of ideas (search starting points)

The concept of a "search starting point" in the design process, as revealed through the above analysis, bears a significant resemblance to the concept of "original thought" discussed in prior literature. Specifically, the convergence of diverse ideas into a defining moment of creativity, as observed in the current study, aligns closely with the descriptions by Dorst and Cross (2001) and Stacey and Eckert (2010). These authors articulate how a "creative event" marks the juncture at which an original thought catalyses the development of coherent and productive solutions to design challenges. This comparison underscores the foundational role of creativity in initiating the search for solutions within the design landscape, reiterating its critical importance as highlighted in earlier research.

In parallel to the process of ideating, designers try to narrow down the search boundaries. We find that the constraint-seeking process is essential for building and narrowing down the solution space.

The data analysis led to the identification of several strategies employed by designers to narrow down the boundaries of the search space and focusing on particular areas within the broadly defined solution space (Table 4-2). These strategies and the strategies for deciding the search starting points are not mutually exclusive, as they both are elements of the designers' creative thinking process.

Narrowing down the boundaries	Evidence from the interviews
Decide the genre and sort of message to communicate	"Before [development stage], you have to understand what it actually is, so for example if this is an art film set in the past, we have got to set the genre-specific … and then you put all these tags word in, and that would be it needs to be at certain style, at certain theme, and these sorts of narrowing process. Unfortunately, how it reads, feels like you are putting all creativity out of it, but it is not, because it is a list of criteria that narrow things down and what that does then, is it stops you from having to worry about things outside of that unless you want to" (graphic designer C, 2013) "There are some genres and triggers that like comedy where white work better so that is just another criteria that we need to fulfil" (graphic designer C, 2013).
Eliminate	"But what we said to him was that there is an area in design that we don't want to go into, this is too far. So, this guy, for instance, is running a serious news site, so he wants to be seen as a serious player

Narrowing down the boundaries	Evidence from the interviews
	at the same level as BBC and ITV.... and he wants to attract new users, but if we want to go too far into saying pop culture or celebrity, or the things you find in many many news, then it is not its brand anymore. So, we already define some boundaries to the brief" (graphic designer B, 2013)
Change perspective	"So, while we received the brief very often all of us will have a look at it, so we sit down and talk about it and try to assess what it needs to be" (graphic designer C, 2013)
Define rules	"So, you need to know the rules so you also can break them or not. Because what you are creating, is something people have an idea of, so if it is a poster for example it has to look like a poster, if it looks too much like a book apparently it creates confusion and people don't get it and if they don't get it straight away it is not doing its job then. That is not about limiting the creativity it is about being appropriate to your audience and saying it is what it is". (graphic designer C, 2013)
Name potential areas	"We have to be able to communicate; we have to have a language. We actually call each of our possible designs by a name. So, we call these the roots, actually in that initial concept presentation, we had three roots … so we named the roots, it helps the client as well it is another kind of boundary or sort of circling the information. You have to define it otherwise we can't explain it" (graphic designer B, 2013)

Table 4-2 Strategies for narrowing down the search boundaries

The analysis presented aligns with findings from prior literature, such as those by Finke *et al.* (1992), who observed that idea generation thrives under tight constraints, making it both fluent and effective. Similarly, Stacey and Eckert (2010) contend that a pivotal aspect of creativity in design involves the deliberate definition of constraints, which serves to give shape and structure to otherwise vague or ill-defined problems.

So far, this discussion has outlined the designers' off-line search process, which encompasses the construction of a mental model of the search space, the establishment of search boundaries, and the selection of a starting point for the search. In other words, the search process, up to this stage, does not include producing a prototype or any type of physical output that can be visually or functionally evaluated. It is only after this *off-line search* stage that designers start building physical manifestations of their ideas and commence the experimental search.

The term “off-line evaluation,” as opposed to “experimental evaluation,” as described in section 2.8.3 has been coined by Gavetti and Levinthal (2000) and indicates choices that are based on a mental model or cognitive representation. Gavetti and Levinthal argue, “cognition is a forward-looking form of intelligence that is premised on an actor's beliefs about the linkage between the choice of actions and the subsequent impact or experiential search of those actions on outcomes”.

Experimental search of the mental model space

Adopting the terminology introduced by Gavetti and Levinthal (2000), as explored in section 2.8.3, the concept of experimental or on-line search is defined as a process whereby understanding the relationship between actions and outcomes is gleaned through the execution of actions and the subsequent feedback received. At this stage, alternatives are evaluated as the result of on-line experimentation. This process typically combines selectionism, or parallel trials, with iterative refinement (Loch *et al.*, 2008). All the companies represented by the interviewees typically generate three concept solutions that are further evaluated by the client. One solution is then selected and further refined. Officially, the client is able to choose the most preferred solution in a formal design review. However, the designers often have a clear preference for one of the three proposed solutions; it is the one they most believe in. In order to ensure breadth of search, they then develop one solution that “offers the client something they are not expecting” (graphic designer C, 2013) and designers feel “it really shouldn’t work”, i.e., it is ambitious and risky (graphic designer B, 2013). The third proposed solution sits in between, i.e., it can be an alternative, but it is not the designers’ first choice. he interviewees believe this strategy offers a balance by showcasing novelty (“in a different way from what perhaps the client had anticipated” (graphic designer C, 2013) alongside a clearly preferred solution that meets the client's needs.

When designers work under a tight budget constraint, they will have to spend less time exploring the solution space and may therefore produce less than three solutions, often only one:

> “It was a mailer, a direct mail piece, I told them the only thing that we can do for this product, is that I have got an idea that we are going to use, as long as you like that idea, then we can do it at that price.” (Graphic

designer B, 2013)

The generated solution is 'selected' from the parallel trials based on the designers' past experience. In other words, they select one concept that has worked in a similar situation in the past, and then they tweak it to fit the new situation. This is consistent with Herbert Simon's (1962) notion about sources of selectivity. Simon notes that human problem solving "involves nothing more than varying mixtures of trial and error and selectivity", while selectivity derives from two basic sources: first "various paths are tried out, the consequences of following them are noted, and this information is used to guide further search … the second source of selectivity in problem-solving is previous experience. We see this particularly clearly when the problem to be solved is similar to one that has been solved before. Then, by simply trying again the paths that led to the earlier solution, or their analogues, trial-and-error search is greatly reduced or altogether eliminated". Loch *et al.* (2001) have noted the importance of the relative cost of selectionism and trial and error learning in adopting either of the strategies for solving design problems. The budget example above illustrates how consideration of cost and available budget can influence the number of parallel trials.

Once a particular solution concept has been selected by discussions among designers and clients, the design is further refined in a very collaborative process. Designers continuously seek feedback from their colleagues as well as their client. In addition, the designers refine the work based on the visual feedback they get from the actual design. The following quotes from the interviews clarify this iterative feedback-seeking process:

> "We will take opinions [from the team] because so much of what we do is subjective, we have to understand that what I see when I create it is the same as the guys see when they see it; that I am getting the message across in the same way as I need to. So, it is the reality check" … "We ask questions of each other and ourselves. First, I will ask myself and say does this say what I think it says?" (graphic designer C, 2013).

> "Sometimes you say I need a blue wall there, then you have a blue wall and say actually it is not very good. So, there is a certain amount of trial and error and refinement." (graphic designers B, 2013).

> “We create something and then we rework it until it satisfies the customer. It is collaboration, and therefore their input is required in order to make the whole solution. We don’t have the whole to give.” (graphic designer C, 2013).

> “These things work by changing the rules because you don’t necessarily associate the colour gold with death, and you also don’t necessarily associate the colour gold with hope, so perhaps you need to try these things and say OK it doesn’t give me a pleasing feeling, so trial and error.” (graphic designer C, 2013).

> “If it looks right, it is right.... and you got to look for balance and proportion.” (graphic designer A, 2013).

The process of refining continues until designers get to the point where they “feel strongly about the solution”: “We don’t want to then go on and keep going because there is not enough money in it” (graphic designer B, 2013). Another interviewee mentioned, “We say to our client that we can amend [the solution] until they are happy” (graphic designer C, 2013). In other words, the graphic design search process concludes not when an optimal solution is identified, but rather when a satisfactory solution is achieved—a concept aligning with the principle of satisficing, as previously identified in the literature by Mihm and Loch (2003) and Simon (1956). This approach underscores the practical balance between aspiration and feasibility, reflecting the concept of satisficing detailed in earlier research.

4.2. A Framework for Describing the Search Process in Graphic Design

Figure 4-1 provides a comprehensive depiction of the search process observed within the graphic design, through a detailed conceptual framework.

SEARCHING THE PROBLEM SPACE

Search to know the problem space via:
- Examining competitive environment
- Knowledge pooling
- Stakeholder analysis

Reframed customer requirement document

SEARCHING THE SOLUTION SPACE

Sources of ideas (search starting point):
- Actual problem
- The materials designers are supplied with
- Competitor works
- Successful examples from non-competitors
- Trends in the industry
- General market trends
- Combining ideas
- Triggers from experience
- Inspiration from other sources

Broad Off-line Search

Search to find a promising solution area and narrowing down the boundaries via:
- Decide the genre and sort of message to communicate;
- Eliminate;
- Change perspective;
- Define rules;
- Name potential solution areas.

Experimental Search

Create and develop the solution via:
- Selectionism
  - Various routes
  - Previous experience
- Trial and error

Figure 4-1 Search process in graphic design

This framework illustrates the approach to identifying problems and searching for solutions tailored to holistic products characterised by their lower complexity. Notably, graphic design projects are marked by their minimal interactive components and are typically executed by small, agile teams. Following this, the subsequent section will explore the design process for a more complex products, highlighting how the approach adjusts to accommodate increased complexity.

5. Case Study 2: Automotive

In addition to the interview carried out with a participant in the pilot study, who shared insights from his experience in the automotive industry, study two included interviewing three design engineers of a pioneering automotive firm. At the time of collecting data for this research (2013), the company had around 29,000 employees across the world, of which 4000 people worked in one of their advanced design and engineering centres, where the three interviewees were placed.

Automobiles are complex products, for example, a high-end car contains about 3,000 parts, many of which interact, through spatial constraints or flows of force, material, information or electricity. The complexity of the products drives a high level of complexity in organisational design, product design and associated processes. Car design projects encompass a broad array of processes and tasks performed by numerous teams from various disciplines; therefore, it requires interaction between many participants, including automotive designers and engineers working on different elements of the design. The selection of and access to the interviewees for this case was rather challenging. While ideally, the research would benefit from interviewing experts from different teams involved in the design and development process, in practice this was not possible and hence the interviews were conducted with available people albeit with extensive knowledge about the entire design process and involved in the relevant activities.

Interviewee 1, worked as the DET coordinator and as part of the advanced design team, where DET stands for Design Enabling Technologies. As per the interviewee, "the job is the interface between the research department at xxxx and the Advanced Engineering department". "I have a direct link into the research department for Design Enabling Technologies, so a lot of time, our design group will come up with interesting visual designs, some element of which need to be achieved through the generation of new technology, and that is known as design enabling because that is technology enabling our design vision". "My basic job is to make sure that we get design requirements in terms of proportions, technology needs, aesthetic needs… and make sure they are correctly communicated to the engineering team and where we have

disconnects that require inventing new technology as opposed to the established way of doing things, so, where there is a genuine need for the invention of new technology, it is my job to get involved and make sure that we specify the requirements in design in a way that engineers can go away and deliver that" (DET coordinator, automotive firm, 2013)

Interviewee 2, worked as the Human Machine Interface specialist as part of the Advanced Engineering team, so when a technology need is defined by the Advanced Design team, interviewee two works on projects to deliver that technology. "Advanced design team is more about the appearance and the experience that the customer gets, then we own sort of technology execution of that… So design vision in its own right generates projects, so, for example, one of the things they (exterior designers) are always looking at, is the A-pillar on the car, between the windscreen and the side of the car, from a design perspective they like to eliminate that, but obviously, structurally that is quite a challenge because you have got the roof, you got the crash, all sorts of things, there is always physical limits to that, so design enabling technology that can help eliminating that would be slim structural beams or maybe a display technology that can wrap around the pillar and display information almost in continuous view, so that kind of thing would be considered design enabling technologies. And at my group, we would look to see what technology is around to enable that so looking to detail of display technology…" (Interviewee 2, automotive firm, 2013)

The third interviewee was working as the Human-Machine Interface Specialist as part of the Infotainment team. The team is responsible for developing technologies to provide audio or video entertainment, as well as automotive navigation systems. All interviewees were able to provide answers to questions that were of interest to this study.

5.1. Search in Automotive Design

Automobiles are complex products, for example, a high-end car contains about 3,000 parts, many of which interact, through spatial constraints or flows of force, material, information or electricity. The complexity of the products drives the high level of design complexity and associated processes. Car design projects encompass a broad array of

processes and tasks performed by numerous teams from various disciplines. Therefore, it requires interaction between many participants, including automotive designers and engineers.

Automotive design (the primary focus of this study, as opposed to technical product development) is mainly concerned with developing the product concept and the visual appearance or aesthetic of the vehicle. Crilly *et al.* (2004) argues that consumers' aesthetic preference is influenced not only by the artistic elements of the design but also by product features; this needs to be considered by designers in striving for an aesthetic impression. Features are defined as the characteristics or a cohesive set of functional behaviours of the product that enhance the appeal of the product to the user by offering them a meaningful service (DET coordinator, Automotive firm, 2013).

Person, *et al.* (2007) explores the role of styling as a strategic tool in product development and marketing and argue that while intuition plays a significant role in styling decisions, complementing it with a strategic approach can enhance product appeal and market success. The authors analyse how styling can be used deliberately to convey specific product attributes, align with brand identity, and meet consumer expectations. Kimura (1997) notes that "From the users' viewpoint, styling is strongly related to product usability and amenity". The success of new products is often attributed to the delicate combination of aesthetics and enabling technology. Therefore, the automotive design focuses not only on the shape and form of the vehicle but on a combination of form and features. The automotive design is therefore holistic. It is concerned with developing the design solution as a visual entity, the impression of which interacts with the features offered. The features and the aesthetic appeal of the car are emotionally perceived and depend on details in a many-dimensional design space. Moreover, the development of features and styling are carried out by separate teams, so the automotive design space can be thought of as parallel, highly interrelated search spaces that co-evolve and converge in order to shape the final solution.

The thesis examined how these search spaces are shaped, how they co-evolve and interact in order to create a new vehicle concept, and how this search process is similar or different from what was observed in graphic design. The focus of the investigation was mainly on the process of developing a new product style and features, rather than

the subsequent engineering design that develops functional embodiments of the designers' proposals.

5.1.1 The Process of Identifying a Problem Space

In graphic design, a project starts when a client approaches the designers with an 'identified problem'. In car design, typically a project starts when marketing recommends a change or an opportunity to the Programme Office, prompted by market research and user evaluation. Projects fall into two broad categories: Re-fresh or updates of existing models, and introduction of totally new vehicles.

Refresh/update projects

A new version of a vehicle (or its subsystems) is largely a response to problems identified in the previous versions, for example, to reduce manufacturing costs or to achieve targeted and well-defined enhancements in the car's visual appearance (e.g., "change the form of the boot lid, bumper or headlights"). In such cases, a project is initiated in order to address an existing problem.

Such projects are referred to as 'refresh' or 'update' and leave the major manufacturing processes and the 'platform' of the car unaffected. The targeted problem that designers are looking to solve is "the need for a new model to look different" (ergonomics supervisor, Pilot case study, 2013). Therefore, update projects do not typically pose complex and holistic design problems. As the designers know that neither the holistic impression of the product nor the technical execution will change (only targeted aspects will), they focus on solving these targeted changes with little iteration (assuming re-design success on the first try). Therefore, I do not further discuss update projects in the remainder of this chapter; instead, I focus on new vehicle programmes, which do have a holistic character (as we explained earlier).

New vehicle programmes

In a new vehicle project, the process is more complex and resource and time intensive, so designers are not initially provided with a very tight brief of what needs to be developed. A new vehicle is a holistic design problem, as the creation of every part of the solution (aesthetic and technical) may potentially affect every other part and the

holistic impression that the vehicle creates. In automotive companies, the creation of a new vehicle is referred to as a "programme" (while the process of updating a vehicle is referred to as a "project") (DET coordinator, automotive Firm, 2013).

As mentioned earlier, typically a new vehicle programme starts with the Marketing department analysing the opportunities and gaps in the market. For example, marketing may examine the size against the cost of existing products and identify whether there is an opportunity for a certain size vehicle within a certain price range. In other words, vehicle programmes are usually generated via "market pull" (what new vehicles does the market demand at the moment). Technology-push exists, of course, also in new vehicle design, but it typically happens at the component level, for example, most new technologies are developed and proposed by suppliers (such as a new fuel injection system, a new brake, or a new headlamp capability). Exceptions are described below.

Once the need to develop a new model has been established, a multidisciplinary team including market researchers, designers, engineers and researchers start a broader and deeper search of the problem space and the product requirements. This is done in respondents' organizations through a formal exercise of identifying trends in designs (e.g., fashions, shapes, and features in luxury products), technologies (e.g., materials, manufacturing process and electronics), markets (e.g., main competitors, customers' expectations and desires in different markets and countries), and government regulations (e.g. safety, fuel economy, safety, customer feedback from past models or competitors, and so forth). Based on these analyses, a proposal for a new vehicle will be developed, often referred to as "product assumption" or "product brief". In developing the product assumption, market researchers, engineers and designers collaborate in defining the intended customer population and understanding their needs, desires and capabilities. In this process, a representative sample of customers may be interviewed (Bhise, 2012).

The feasibility of these very initial ideas is confirmed in principle by design, engineering, and manufacturing; so, for example, manufacturing might say, "If we hold this distance constant, then we don't need to change our investment in our plant beyond a certain amount, so we might be able to do this" (ergonomics supervisor, pilot study, 2013). Thus, the feasibility discussion is more formal than in the case of graphical design:

a difference that reflects higher complexity, as the larger number of interactions among players in the design, demands more coordination.

Thus, adjusting for complexity, this process is recognisably similar to what was observed in graphic design. Marketing acts as the customers' representative, comes to the programme office (which includes representatives of development teams) with a series of identified problems and suggests a need for a new project or programme. The problem is more deeply explored and re-framed with input from design, engineering, research and manufacturing. The typical activities in this stage include identifying main competitors, defining market segments, identifying key users and the features and functionalities that they may need, the target market regulatory requirements, and an initial feasibility assessment. At the end of this stage, the product 'brief' or 'assumption' is prepared in written form (using the consumer's language, as in graphic design), consisting of a description of the vehicle type, market segments, and desired product characteristics and features. The product assumption is continuously updated as the team gathers new information (Bhise, 2012).

5.1.2 Decomposing the Problem and Identifying Associated Solution Spaces

When the product brief is released, the next step is defining the critical "attributes" of the vehicle. Attributes are defined by one of the interviewees as the "primary characteristics of the vehicle that the customer can relate to". Examples are fuel economy, hybrid performance, driveability, serviceability, ergonomics, weight, space, styling, etc. (ergonomics supervisor, pilot study, 2013); or as described by another interviewee:

"An attribute is for example capabilities on-road and off-road, it is not about the solutions but about performance characteristics, so the overall performance of the car relates to the performance of the engine, the performance of the comfort of seats, the performance of the ergonomics, ... so without coming to technical solutions we can define as a company from previous cars how good this has to be... so they will define the functional and non-functional requirements, the engineering team then actually say how much of that functional requirements can they meet" (DET coordinator, automotive firm, 2013).

Kokkolaras *et al.* (2002) note that for developing a complex product, setting up attributes and enforcing proper specifications for each of the attributes is a necessity. Kim *et al.* (2003) identifies four steps in target setting and 'cascading' in automotive vehicle design, of which the first two steps are related to understanding the problem space, and to defining the search spaces and initial constraints, and the next two steps relate to the actual search for the solution within the identified spaces:

1. Specify the overall vehicle mission targets,
2. Cascade vehicle targets into subsystem and component's sub-targets,
3. Design vehicle systems, subsystems, and components to achieve their respective sub-targets, and
4. Verify that the resulting design meets the overall vehicle mission targets.

Defining the top-level attributes has two key implications: first, a complex problem is partitioned into sub-problems, each associated with a configuration of system and sub-systems that can address that attribute (design problem); and second, the overall characteristics of the associated solution space are identified, in effect defining this solution space.

Decomposing the problem space and identifying the architecture of functions and performance requirements directly reflects the complexity of a vehicle, which poses a system engineering aspect in vehicle design that is not present in graphic design. In a system engineering approach to product development, target cascading is introduced at the early stages of the development process and in the system definition stage. This phase includes target setting, formulation of design problems at various levels of a modelling hierarchy and suggestion of the design architecture (Kim *et al.,* 2003). The systems-driven approach to car design brings all aspects of car design together in a holistic fashion and makes it easier to meet requirements throughout the design process with regular validation.

A car design typically does not have more than 15 top-level attributes (ergonomics supervisor, pilot study, 2013), which are defined by a so-called "attributes team". The existence, importance and character of each attribute may vary across products and

markets. On each attribute, the attributes team chooses the level of competitiveness it desires to achieve, which may in the studied cases be 'best in class', 'leadership', 'amongst leaders' or 'competitive'. The identified attributes define the overall vehicle mission targets in marketing language. In summary, in this stage, the brief is further refined, and it is more clearly defined that what client's needs can be met, but not how.

Once the top-level attributes are defined, each attribute is allocated to a team or a number of teams and is broken down by them into lower-level characteristics or targets (an example is shown in Figure 5-1). It is the responsibility of designers and engineers in those teams to deliver a solution that eventually fulfils the desired attributes (but they must coordinate with other teams in order to manage interactions, as we describe below).

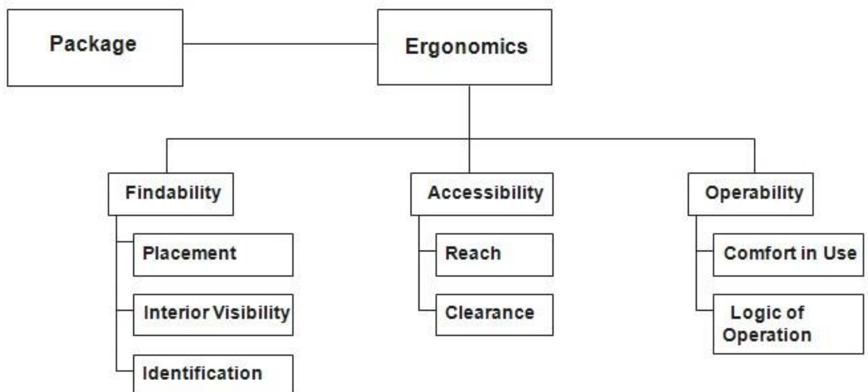

Figure 5-1 Example of sub-structure of one top-level attribute

Systems, subsystems, and components need to be configured such that they deliver the cascaded characteristics that contribute to the top-level attribute(s) and the overall car vision:

> "Usually, the attributes get delivered by a number of components that Engineering controls, they [the attribute team] normally set functional performance on the system level and Engineering might set performance requirements for a part. So, for example, the attribute people say it has to feel in certain ways, this key has to feel wobbly, the engineers say it has to last 50,000 presses" (ergonomics supervisor, pilot study, 2013).

However, the car attributes are highly interdependent. For example, fuel economy and weight are interdependent, or styling influences the fulfilment of packaging requirements. Thus, different teams cannot simply work independently alongside one another to develop the 'part' of the solution they are responsible for. Moreover, many attributes are influenced by multiple subsystems, for example, comfort depends on the driver assistance systems as well as on the design of interior comfort systems.

Finally, interactions among attributes cause trade-offs: attributes might be in conflict with each other. Therefore, automotive firms need to establish the best fit between a vehicle's optimal mix of attributes and customers' requirements and preferences. These trade-offs are highlighted by one interviewee:

> "As a company, we will have a number of attributes, all of which might be in conflict, for example, we have to tweak the design attributes so much that the seat becomes more comfortable...at the attribute level this is managed by an attribute leader... the attributes will be tuned so that a car has great off-road capabilities and great design, but on-road may not be as good as this and we literally and knowingly have these sorts of levels so that they can turn to product level performance" (DET coordinator, automotive firm, 2013).

The attribute team works with designers and engineers to manage the trade-offs (DET coordinator, automotive firm, 2013).

Summarising, there are clear similarities as well as differences between the search processes in graphic design and automotive design. Similarities can be observed in the identification of the problem space: in both cases, customer needs are identified, although from different sources (from a client request in graphic design, in contrast to automotive design, where customer needs arise from market gaps identified by marketing people). Again, in both cases, the problem is explored by producing a draft requirement document, which is then reframed based on feedback from customers (or marketing as their representative) and solution developers (i.e., designers and engineers).

The processes differ markedly between graphic and automotive design in the solution space identification stage: the complexity and hierarchical structure of the requirements in automotive design imply a hierarchical structure for the solution spaces. Consequently, the system cannot be designed and developed independently by a small team searching a limited solution space. Rather, multiple teams search subspaces, but the teams have to continually coordinate (and possibly iterate) because of interactions between the solution subspaces. It is well known that these coordination and iteration problems can cause “design cycles”, or a repeated “dance” of revisiting components because the interactions force the teams to backtrack (Mihm and Loch 2003).

This complexity also increases the planning time in automotive design as compared to graphic design: the planning of how to search the identified problem and solution spaces takes six to twelve months, a time frame that is so long that the attributes and performance requirements may not remain constant but co-evolve with the solution.

In this process, *four* steps were identified: first, identifying the problem space; second, reframing the problem in a collaborative process; third, partitioning the problem and further refining the requirements; and finally, identifying the broad shape of the solution spaces.

5.1.3 The Process of Searching the Coupled Solution Spaces

After re-defining and partitioning the problem space, and identifying the broad solution space characteristics, the design and engineering teams start searching for the solution within the defined solution spaces. This study focused on understanding how the aesthetic impression (as opposed to the technical execution of attribute fulfilment) of a new vehicle is developed via evolutionary search in multiple coupled spaces. This includes the process from an initial conceptual design in the form of sketches to a fairly detailed design in the form of a clay model with defined surfaces and design features before engineering assumes control. The whole process takes about 18 months and is described as follows by one of the interviewees:

> “For a full vehicle program, we take around 4 years. We do what we call ‘Stop Clay’ and from the beginning to that point will be around one year and a half so if you tell designers to start sketching cars from that day will

be around one and a half years until we have a final theme and after that time it is just feasibility checks where we concentrate on very very fine details like a seal on a door or slight curvature really. So, when the creative part of the design is complete, we then try to make that creative design real…it is then more delivering that design with engineering teams” (DET coordinator, automotive firm, 2013).

The process happens in two broad stages, parallel search in individual search spaces and finding, creating and controlling interdependencies among spaces. Concerning the aesthetic appearance of the car, the first stage of the process consists of a creative generation of the overall themes. The themes get further refined, rendered and evolved in detail as a result of interactions with other solution spaces.

5.1.4 Parallel Search

Creative generation of the overall design solution

Once the programme’s top-level attributes are laid out, a rough outline is provided to the design studios. The studio manager calls a meeting of all stylists and modelling supervisors, informing them of the requirements. In this meeting, the designers discuss the requirements and explore possible solution avenues in a brainstorming exchange of opinions and ideas.

In principle, each team will start exploring its own problem space (e.g., designers the exterior, the chassis team the axles and drive train, the interior team the passenger cabin and so on), their work going on in parallel. However, typically, the exterior design is the first (or first priority) process to be initiated (except for the first new car that starts a new platform, where interior design proceeds in parallel), as the exterior is what “defines the segment or the market opportunity of the car” (DET coordinator, pilot study, 2013). The designers (also known as stylists) have the responsibility of creating the initial conceptual design of the new vehicle. In the words of the interviewees:

> “These initial sketches, typically performed with paper and pencil, are the first stages and essential part of the idea generation side. Idea generation will go through a process of filtering and then iteration to kind of refine that idea to

something we communicate to teams… and there is a competition for that… each designer has their own file of designs that they work on, and then senior designers work with them to refine their ideas to a certain point, where we have a design review…so it can be up to 3 o 4 designs a designer might have but they will only release to everyone else or share one design which they think is the strongest…so at this stage, designers propose their design against everyone else's…(DET coordinator, pilot study, 2013).

In parallel to Table 4-1, Table 5-1 summarises sources of inspiration for a vehicle style. As none of the interviewees was a stylist, it also includes secondary data (from interviews with exterior/interior designers from Motor trades Insight Magazine Online). The secondary data have been corroborated by one of our interviewees.

At this stage, the sketches are loose and unconstrained. Accuracy at this early stage is not a prime goal. The key point at this stage is to develop a basic concept and portray a visual message for sharing the designers' mental images of the possible solutions. Ideas that previously existed only in the designer's head become visible through sketching.

Sources of ideas	Evidence from the interviews
Inspiration from other past experiences	"Designers may come from a different background, not automotive, so they may go to big design conferences or even art exhibitions which are not necessarily related to our industry like 100% design" (DET coordinator, automotive firm, 2013)
Trends in the industry (Exhibition/magazine)	"To be inspired for new vision cars I go to things like tradeshows, read magazines, occasionally someone will send me some artworks…So if I go out and see something that I get inspired by and think we can develop that to a sort of concept or vision I will come back to the design team" (DET coordinator, automotive firm, 2013)
Trends in other industries	"There is always an element of benchmarking, so traditionally within the organisation benchmarking has been looking out at what we consider to be adjacent sets ... i.e. other key automotive manufacturers, however, I would say that this has changed very recently because with the acceleration in bringing technology into the market, we actually have to look more at the mobile device industry and learn from them..., you also have got marine design, aviation, there are lots of industries that are close to us and up until recently the industries would have been most segregated, I think as we are moving forward there is a lot of cross over across industries, there is a lot more influence, there is a lot more looking to other areas and other

Sources of ideas	Evidence from the interviews
	industries and say what we can learn from that, that we can do differently" (infotainment specialist, automotive firm, 2013).
Combining ideas	Inspiration is all around you, often staring at you right in the face. You must have the gift of 'vision', and this is very difficult to teach. It has to come naturally, and it has to be fun, a part of you. Future fashions are not predicted. They are simply executed. Look into directions where no one else does, find combinations, and sometimes just be random (David Hilton, Head of Exterior Design for Bentley, 2013)
Inspiration from other sources	I have several such examples [on the source of inspiration]. My favourite is the roof element on the MC1 Supercar. I was lost as to how to resolve this roof-cooling intake and its several parts coming together. … I know this is going to sound cliché, but it actually happened: while desperate for this solution, I went to a classical concert within a very old cathedral in Cologne. There was a violin solo accompanied by a 20-person string backup. It was great. I closed my eyes and tried to visualize what that music might 'look like'. The movements, the fluidity, the sharpness and fullness. And then bang! Something started to form, my two worlds came together, and I started to visualize my many parts coming together in a way, which was shaped by this music. It was only a glimpse into the solution, but that inspiration helped massively. I was not 'trying' to find a solution that night, it just happened because I relaxed. I think you can see the instruments and musical forms a bit on that roof (David Hilton, Head of Exterior Design for Bentley, 2013)
Successful examples from non-competitors' work	"Personally, I get my inspiration from the consumer electronics market. Simple things like the iPhone can inspire a lot because it is a simple black surface, all gloss and it has a nice chrome metal frame around it. When you think about what premium-ness it supports to your eye, you can treat it in a different way and go for black high-gloss surfaces and then you add some jewellery element on this high-gloss surface to add contrast, giving you a premium effect. This, together with the technology and the screen that has a shiny look, gives you a real feel of the next step into the future. So, all the consumer electronics products are, for me, an inspiration – including the general architecture in furniture design" (Ernst Reim, Chief Interior Designer for Ford Europe, 2013)
Previous work	Actually, the inspiration of that car [Icona Vulcano] came from the fuselage. The fuselage, which we did two years ago, was an aerodynamic car to be electric. And the design language which we developed for it is the base and foundation of this car (Samuel Chuffart, Icona Vulcano designer, 2013)

Table 5-1 Sources of ideas for car stylists (search starting points)

A great deal has been written about sketching. It is known to be an essential thinking medium and a powerful tool for designers to communicate their mental models of

problem and solution spaces to team members (Fish & Scrivener, 1990; Arnheim, 1993; Menezes *et al.,* 2006). Sketching facilitates design problem formulation and solution exploration in terms of functions and forms (Goldschmidt, 1991). Fish and Scrivener (1990) mention sketching is conducted not only to clarify existing ideas but also to develop new ones. It also helps in amplifying the designer's "ability to perceive or imagine many options". Tovey (2002) refers to sketching as "visual thinking" and adds that the primary purpose of the sketching activity is to "enable the designer to identify clues that can be used to form and to inform emerging design concepts". Smyth and Wallace (2000) note that through styling designers define "the beginning of an evolutionary process". In short, sketching helps the designers to explore the solution space globally and to identify promising areas and starting points for search.

However, the styling process is not left solely to the intuition and creativity of designers alone. Running up to a formal major design review, the sketches are refined with inputs from managers:

> "The pure sketching stage can last from one to three months really. Structurally you have the designer level, then their manager, then you have the senior creative and then the studio manager and then you have the design director, so during the sketching phase, we have reviews at different levels through that process. The design director probably will only perform one review, but the studio manager might see a designer's work three or four times in that process, because it is a design studio, they sit just with you and say, let's see what you have got, very informal, and they give direction" (DET coordinator, automotive firm, 2013).

The formal design review selects three to five sketches to go to the next stages; the selection is based on the design director's subjective analysis of the sketches:

> "So the competition sort of runs in the design generation and the creative design part of the process, and it is primarily based on what the design director sees as the most appealing sketch from a design perspective … after the initial sketching stage, we pick different concepts and we progress into basic package feasibility and then Alias, which is a 3D modelling software and the progression

of it as a theme or as a style is based on the design director's point of view in the first step" (DET coordinator, automotive firm, 2013).

Apart from agreeing on preferred themes, particular features might be perceived as desirable and worthy of inclusion in future sketches (DET coordinator, automotive firm, 2013).

This observation aligns with the insights presented by Person *et al.* (2007), who posited styling as a strategic instrument in product development and marketing. They contest the view that styling is merely an intuitive, "touchy-feely" activity dependent entirely on the creativity of designers. While acknowledging the critical role of intuition and personal creativity in the success of products and brands, the authors argue against leaving the designer and the styling process without managerial guidance.

The styling design up to this stage runs fairly independent of the design of other systems, in order to enable the formation of creative ideas and to ensure the breadth of search. This phase is the "emotional phase" of the design process and is "necessary for exploring the creative potential of a new vehicle project and steering the different design ideas into the right channels" (Mercedes-Benz – Latin America, 2013 At this point, the design remains highly conceptual, with design details and feasibility constraints not yet considered (DET coordinator, automotive firm, 2013). The primary consideration for designers during this phase is often the vehicle's DNA or design genes, which encompass a predefined set of characteristic lines, proportions, and elements established by company standards (DET coordinator, pilot study, 2013; Pfitzer and Rudolph, 2007). This approach aligns with the findings of Person *et al.,* which suggest that strategic decisions on styling are framed within three dimensions: decisions regarding the current product portfolio, the progression of product generations, and the positioning relative to competitors' products.

Typically, sketching is followed by a more detailed concept drawing and a very precise rendering, as more accurate outlines will be required before the process can proceed to 3D modelling. After the first sketches, the very loose phase is terminated. Adding details and accuracy strongly depends on the constraints and requirements imposed by other subsystems, such as the vehicle package.

Parallel evolution of other subsystems

In parallel to the exterior design sketching, other teams work simultaneously on different aspects of the vehicle. Each team searches within its respective search space, develops alternative solutions and gradually narrows them down and improves them, iterating based on additional information received or constraints imposed by other teams. However, "in the first aesthetic appraisal, there are not that many points that relate to the work of different teams, like interior or exterior together" (DET coordinator, automotive firm, 2013).

For example, the packaging information is one of the constraints (and indeed one of the very early ones) imposed on vehicle styling (ergonomics supervisor, pilot study, 2013) and normally is published by a so-called 'Studio Engineering' team early in the project, right after the initial sketch-work phase (DET coordinator, automotive firm, 2013). "The 'package' is the industry's term for the three-dimensional (3D) view, full-sized orthogonal drawings which show the space requirements of the mechanical and ergonomic requirements of the intended vehicle. They are produced by an expert team of layout engineers and ergonomists, in consultation with product planning and styling" (Birtley, 2002). It characterises the space allocation for various vehicle systems and accommodating people and providing storage spaces for the users (Bhise, 2012). The initial guideline (the starting point of the search) for the package engineers is specified by lists of dimensions from past vehicles, plus full package drawings of competitively relevant vehicles. The package drawing, with its dimensional data, provides the basic dimensional controls for all other developments in all departments, including styling (Birtley, 2002). Similarly, other technological features evolve and are integrated to form the aesthetic output. The following section describes the process in more detail.

5.1.5 Convergence, Trade-Offs and Coordination

Finding and creating interdependencies among styling, packaging and structural engineering through 3D modelling

Car companies use two main types of models in order to evaluate component and subsystem interdependencies and aesthetic impressions. The first is computer-based modelling, and the second is a clay model.

First, computer modelling is used to merge sketches with 3D package data and hence give the themes 3D dimensional support. The process "allows for the definition of mathematical curvature and surface analysis and represents a basis for the subsequent engineering compartments working on the more technical aspects of the car" (Birtley, 2002). In this process, the sketches are scanned and imported into the software; 3D surfaces are created based on this 2D input. The software allows placing sketches (in digital form) over-engineering dimensional data to ensure design feasibility. The 3D surfaces are iteratively refined in order to meet packaging constraints. For example, the position of the doors or the height of the roof may need to change with consideration of the position of occupants in the package drawing. "Further to that, 3D models of the designed interior are created, and they can be used to more accurately understand constraints versus package" (DET coordinator, automotive firm, 2013). The stylists continually adapt their solutions in response to the emergence of new constraints.

Body engineering is another function that is considerably affected by styling decisions. The main engineering feedback to styling is provided at the 3D modelling stage, when designers and engineers define the interactions between their respective search spaces. One of the interviewees explained this further:

> "The engineering team will assess that [digital model] from a feasibility perspective and say what mechanical structure is required to build it, like, are the pillars right, does it meet standards, and that would kind of generate massive amounts of iteration and they [designers] go away and think I will need to change that, that and that" (HMI specialist, automotive firm, 2013).

Computer modelling also enables designers to quickly take several concepts from sketches to 3D models and explore details. Hence, it enables a breadth but at the same time more precise exploration and evaluation of the landscape than would have been possible at the sketching stage.

The software also enables the repositioning of surfaces and adding decorative features, a fast presentation of the more detailed design alternatives. In other words, the search space narrows as a result of incorporating engineering constraints, but at the same time, the granularity of the space increases as more details are added.

The models are iteratively refined and visually and measurably evaluated until both aesthetic and engineering constraints are satisfied. They are then reviewed by a fairly large group of people, involving engineering, styling and marketing, and a verbal presentation will most probably be made by a studio manager. The modelling set may or may not be narrowed down at this stage for proceeding to the next stages.

Second, clay models provide a "very realistic impression of the new vehicle's – exterior and interior – visual and ergonomic appearance (Weber, 2009):

> "After that time [3D modelling] maybe two or three virtual models get turned into clay models and then designers start to tweak and iteratively refine the different lines in the vehicle and start to introduce more details to the car, play with the grill for example … and start to refine in reality what does it look like because when you work virtually you can't judge the volume and proportions of the car. A lot of what people appreciate, they probably don't understand until they see a vehicle on the stand and see how it sits on the ground (DET coordinator, automotive firm, 2013)

The designers and clay modellers work closely together in developing the clay models, adding an aesthetic character to the models in order to make them more attractive for the reviewers, who in the end select the final design that proceeds as the 'production' clay model. The component engineers may also add further details to the design at this stage. Any change implemented on the clay model is fed back into the 3D modelling.

So again, at this stage, the search space is further explored, and adaptations are made in response to more detailed information and visual feedback. "The whole process is very collaborative and iterative" (ergonomics supervisor, pilot study, 2013) until a design emerges that satisfies all constraints. This solution might be a "compromised" solution as seen from the pure styling viewpoint:

> "A lot of time the initial design intent may have been much greater… but we may end up with a slightly compromised solution in our view… in design studios, we have the various sketches, the true version of what we wanted that car to be; we know where we came from when we get to car launch. We are normally

pretty happy with it because the engineering team works very hard to help us get the style that we want, I don't think we ever approach the sign-off and go aah. What is important is when your customer sees the model for the first time … they will never know where we were in a lot of aspects before that and where we set the initial design target" (DET coordinator, automotive firm, 2013).

A formal review evaluates the clay works for final approval. This review not only checks the visual appearance and feasibility of the product and conformity with functional and non-functional requirements but also assesses the desirability of the product and its success potential in the marketplace. Therefore, client input is essential at this stage.

Such an evaluation resonates with the insights presented by Crilly *et al.* (2009), who explore the factors influencing product form and its capacity to evoke particular responses from consumers. They argue that beyond the aesthetic appeal, the product form is determined by a variety of factors including functionality, ergonomics, manufacturing constraints, and the intended emotional or cognitive response from consumers. They note that understanding the consumer's perspective and the broader context in which a product is used is crucial in shaping product design. Highlight the complexity of design decisions, they suggest that designers must balance multiple considerations to achieve a product form that not only aligns with the brand's objectives but also resonates deeply with consumers on both emotional and functional levels, ultimately enhancing the user experience.

In the context of the automotive company explored in case study 2, the final selection procedure is intricately structured into three phases: 1) a clay model is selected (out of three), 2) designers are again called back to suggest variations of the selected concept, (themes) 3) a final theme is selected and approved for production:

"After that point, we will pick one concept to work with and then what we do is open up again with more designers so, for example, we look to work with a minimum of two different clays we are going to go with here, and then we get a number of designers to come to that design just redrawing some more details around it, so they may be investigating the headlight and new front face of that

vehicle so this will then open up again for new ideas and then we iteratively come down to sort of headlamp and grill in more themes and that will form our sort of go for one design we call, so we finish that and we go for one and progress with much more details with the engineering team" (DET coordinator, automotive firm, 2013).

In other words, a more detailed "local search" is carried out in this stage "locally" around a chosen design, in order to find further aesthetic improvements. This final local iteration is a typical element of search processes.

Trade-offs and co-ordination

In many cases, the selected concept embodies significant trade-offs among attributes, meaning that there are conflicts between aesthetic design requirements and engineering and functional requirements, which cannot be resolved without one side experiencing reduced performance.

"Sometimes this performance requirement from design will be in conflict with the functional requirements from the engineering team, and then the attribute team decides which one is more important, and most times, there might be a debate that lasts for quite some time because it can be quite an emotional debate because a designer thinks that the most important thing is to have this little fillet, and the engineering guy says ya, but the customer sits on that" (DET coordinator, automotive firm, 2013).

In case of a conflict, either the designers need to considerably change their design in order to move towards the engineers, or they have to look for features that enable bridging the conflicts. Conflicts related to the implementation of the plan sometimes might trigger a search for new features, which enable the proposed car vision:

"A lot of time our design group will come up with interesting visual designs some element of which need to be achieved through the generation of new technology, and that is known as design enabling because that is technology enabling our design vision… so a design vision in its own right sort of generates projects… for example one of the things designers are always looking at, is the A-pillar on the car, between the windscreen and the side of the car, from design

perspective they like to eliminate that and just have one wraparound, but obviously structurally that is quite a challenge because obviously, you have got the roof, you got to crash, all sorts of things, there is always like a physical limit for that it can disappear, so design enabling technology is to help eliminate that. This might be slim structural beams or maybe a display technology that can wrap around the pillar and display information almost in a continuous view, that kind of thing. And my group would look what technology is around to enable that, looking into details of display technology, and somebody in the body team would look at the mechanical material strength that can deliver this beam" (HMI specialist, automotive firm, 2013).

In other words, if during searching the landscape a barrier is encountered (e.g. "A-pillar not feasible for stability reasons"), and then an additional search is done, in the technology group, in order to loosen mechanical constraints. Thus, the search does not just walk around the landscape that is taken as given, but the search tries to change the landscape in critical cases where the desire to go for higher performance is very strong.

5.2. A Framework for Describing the Search Process in Automotive Design

In comparison with graphic design, the search process in automotive design is much more complex and requires search in multiple spaces, which are, moreover, interdependent (except in very early stages). Therefore, developing a holistic solution needs continuous dialogue and adaptation among spaces to find compromises. For the development of the aesthetic appearance of the car, which is of emotive and subjective value to customers, the search can be considered to incorporate two broad stages. 1) a broad solution characterisation via a creative and then eliminative development of mental models, for which sketching can be considered as a tool for communicating the stylists' mental models, and 2) experimental search of a much more constrained space, through communicating mutual interdependencies, coordination and adaptive convergence. These two steps are further elaborated on below:

1. The process starts with a parallel, off-line search of the global landscape. In effect, individual designers act as hikers looking across the landscape for high peaks. At this stage, they have minimal knowledge about the fitness function. Initially, these

search spaces are considered independent and non-overlapping. The pattern for this preliminary search stage is very similar to what was observed in graphic design. It starts with a creative generation of mental models, which helps designers to choose the search starting points and the overall characterisation of their proposed solution; the process is then followed by an experimental search of the mental models through parallel trials, iterative refinement of design proposals and selectionism. For example, numerous sketches are created and iteratively refined with the help of feedback from more experienced designers, who have better knowledge of the landscape and the fitness function. Iteration and feedback loops enable positioning sketches closer to their nearest performance peak. Some designs are deemed better performing than others are; less performing designs are removed. At this level, the landscape is perceived as stable (because no constraints from other aspects of the car are yet taken into account). The output of this stage is a manifestation of (selected) designers' models of the solution space in a mode that is communicable to teams.

2. Each team communicates the model of its search space to the other teams and to the attribute team as the arbiter. At this point, the teams learn about mutual interdependencies and new emergent constraints, and they seek reconciliations and compromises across the respective search spaces. As new constraints emerge, those designs are selected that can survive under the constraints of the emerged environment. Thus, the search agents (the designers and engineers from the various teams) try to adapt their position in order to place themselves in a "common" area of possible compromises. As the convergence process starts, each team periodically updates others on its solution space characterisation and collects information about others; in this way, the teams repeatedly refine their position, under prodding and help from the attribute team. In other words, the different teams "learn" about the overall performance function and seek out designs that perform well overall.

The attribute team comprises experienced designers and engineers with a deep and holistic knowledge of previous performance functions and their interdependencies among design variables (and thus they have good hypotheses about the current performance function). Thus, the attribute team guides the adaptive movements and

the negotiation of trade-offs among the other teams. As a consequence of these trade-offs, teams usually "satisfice" rather than "optimise", i.e., they adopt a solution that is slightly worse than their optimum solution. Loch *et al.* (2003) have pointed out that satisficing is a reasonable way of saving on iterations and time in the design of complex products.

In situations where there is no common ground between teams and their search spaces, or the search teams resist changing their positions, the attribute team decides which teams need to move their design positions so that a narrower, converged search landscape is formed. The guiding role and the 'design freeze' control of the attribute team reduce the number of trial-and-error cycles by the multiple teams in finding an overall solution that everyone can live with. The repetitive communicate-coordinate cycles lead to the growing convergence of the solution spaces until a holistic solution emerges that can satisfy all constraints. In the worst case (if the teams cannot find a common solution), bringing new technologies might help the teams to get "unstuck" by removing some key interdependencies or constraints; as we have mentioned earlier, the search can in such cases change the performance landscape (but this is expensive and risky, and therefore rare).

Figure 5-2 provides a summary of this process in a conceptual framework that is comparable to the graphic design search process depicted in Figure 4-1.

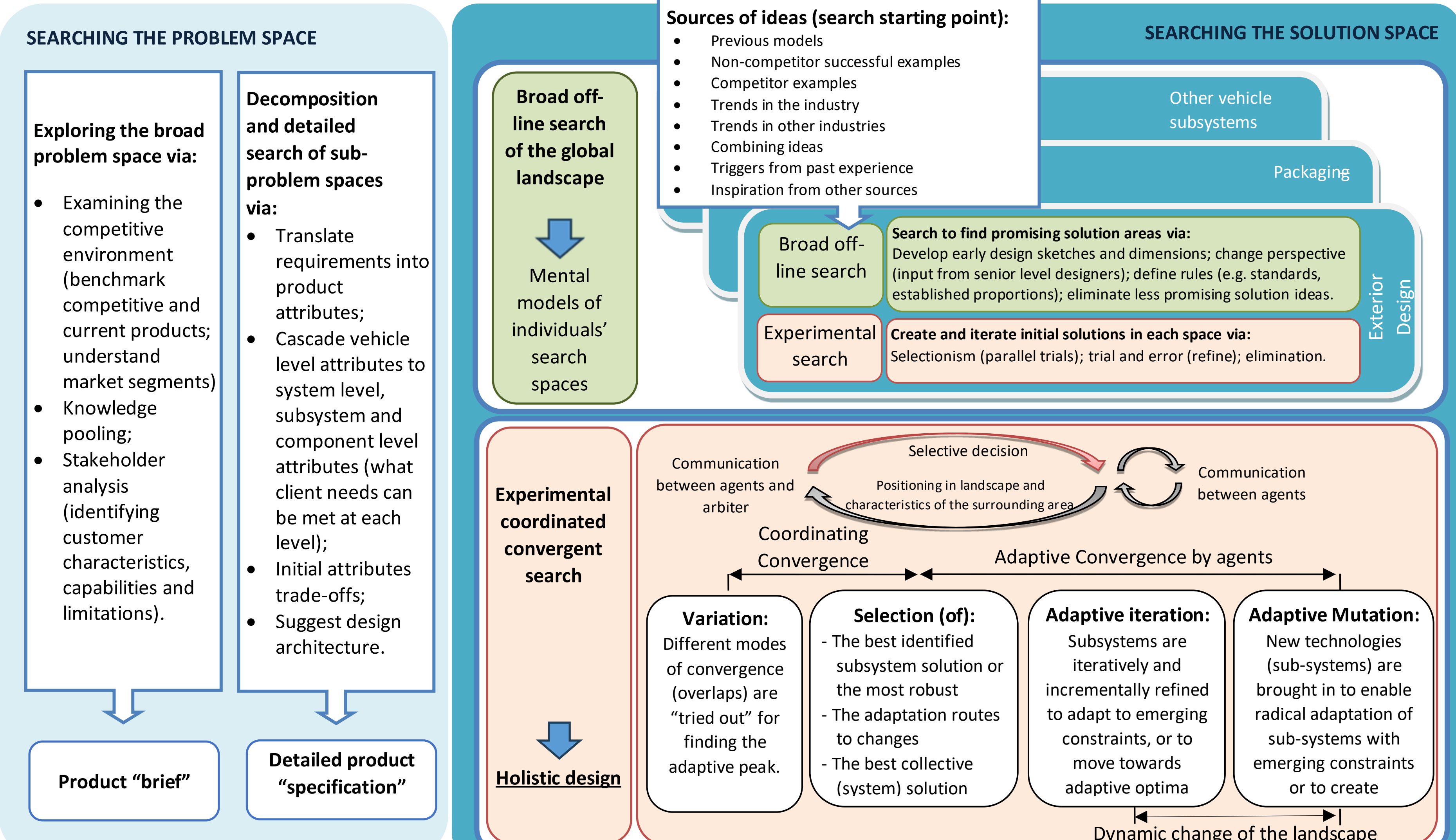

Figure 5-2 Search process in automotive design

A comparison of the two frameworks suggests the following differences between search in graphic design and search in automotive design.

- There is a system engineering aspect in vehicle design, which requires the decomposition of the problem and solution spaces, so initially, there are multiple parallel spaces as opposed to one.
- There is a need for coordination cycles between concurrent search processes in the experimental search stage, as the parallel search teams coordinate their respective solutions to make them compatible and achieve convergence.
- The interactions among numerous components create a very ''rugged landscape''. The landscape is also dynamic: search can change the landscape intentionally (by introducing new technologies or components) and unintentionally (by moves that result in change propagation).
- Compromises across the search teams are brokered by an "arbiter", in the automotive companies' case the attributes team.
- Once a holistic solution has been achieved, each team can still perform a local search (within the constraints of not affecting the other teams) to fine-tune its own sub-system solution.

6. Case Study 3: Small Domestic Appliance Design

Study three included looking into the design of medium complex products. For this purpose, the Household Appliance design was selected. The selection of the sector was due to the background of the researcher in this field, which supposedly could facilitate understanding of the data and asking more targeted questions during the interviews. Three designers from two design consultancies involved in the design of small domestic appliances were interviewed. Both companies had dedicated teams of engineering designers as well as industrial designers.

The first interview included interviewing the creative director of a small design consultancy. The company has been involved in projects to design a range of small appliances including, toaster, coffee machine and kettle. The design section of the company has been made up of two small teams of industrial designers and product designers. In terms of the office layout, both teams were placed close together in an open-plan office area. This arrangement has enabled the engineer/s and designer/s involved in a project to communicate from the very earliest stages of the design process. As per one of the interviewees, the close communication allowed the design team to "integrate both technical requirements and 'emotive' aspects of the design" and make a balance between them (creative director, design consultancy A, 2014)

The second interview was conducted with a design engineer and a product engineer from a medium size technology and product development consultancy. The company is involved in developing design solutions for clients from the consumer, healthcare, energy and industrial sectors. For the consumer sector, the company has delivered projects on developing appliances, consumer electronics and FMCG packaging, right from consumer insight to product launch.

For each design project, an engineering lead and a design lead are assigned. The two work closely together throughout the design process. Although, unlike the previous case, and due to the size of the company, the industrial designers and engineers do not sit in the same room. However, they have frequented joint sessions and meetings to exchange ideas and thoughts. In particular, in the early stage of the process, they go through a long joint brainstorming session:

"To start we brainstorm in a room we sit together, so the initial brainstorm is like a half-day process and all of us being in the same room, and everybody is putting down what is in their thought asking questions like technically how would you operate this and then how that visually impact on the outer looking and how could you use it etc… So, we all work in the same table. So at least you are in a similar mind-set" (product engineer, design consultancy B, 2014).

Having a joint meeting with the industrial designer and the design engineer in this case, enabled the responses to the interview questions to be multi-perspective, and complementary resulting in a very efficient and insightful discussion.

6.1. Search in Design of Small Domestic Appliances

In consumer household design, companies that can provide a subtle combination of aesthetics, functionality and ergonomics (related to ease of use) can create a competitive advantage in the market and increase the product's chance of success (Creusen and Schoormans, 2005). It is argued that the product appearance can communicate messages and certain meanings to customers not only about the aesthetic and form of the product but also other values, including symbolic value, functional characteristics and ease of use (ergonomic value). Hence, the meaning that is communicated through the appearance of a product helps consumers to assess the product on functional, aesthetic, symbolic or ergonomic motives. These motives interact in nontrivial ways and play a role in the overall product appraisal of the product (Janneke *et al.,* 2009). Thus, the design of household products is holistic.

the design of such products requires developing a 'product form' representing one solution to a set of design goals and constraints enabling the "definition of certain experience" for a customer. Hence, in the design of domestic products, the emotive elements of design are very important (creative director, design consultancy A, 2014).

The thesis examined how industrial designers and engineers work together to create a product which is mainly perceived by its appearance (although the appearance conveys different messages as discussed above).

8.1.1 The Process of Identifying A Problem Space

The companies studied in case study 3, were design consultancies. Similar to graphic design, in design consultancies, a project typically starts when a client approaches the designers with an 'identified problem'. However, one of the interviewees stated that there might be cases where they work on ideas until they "come to a point to say that this is how the idea would look like and then go and market it to brands" (design engineer, design consultancy B, 2014).

The case companies were involved in a wide range of projects; some of them were out of the interest of this study. For example, as mentioned by one of the interviewees:

> "There are a series of projects where the industrial design is not going to affect the functionality of the product; a kettle is probably one of them. Because we have designed so many kettles in the industrial design stage, I know that I cannot work below a base diameter of 150ish." (creative director, design consultancy A, 2014).

Such projects are similar to refreshing/update projects in automotive and hence not considered holistic design problems.

Like the previous cases, the starting point for the process of searching in the problem space is the identification of a need or a problem by the client. The problem is then redefined and reframed in a collaborative and iterative process with inputs from the customer, engineering and design teams. Redefining the problem also involves understanding the completive environment and, in some cases, conducting further user need analysis.

The collaboration and knowledge exchange between engineers and designers, to discuss the possible trade-off between engineering feasibility and aesthetic features of the products that might influence the product brief, happens through a fairly informal process. The output of this process could be either a project brief (for simpler projects) or a product specification document if the product is more complex.

Similar to automotive design, if a product is more complex a product specification document will be prepared; this includes information about problem decomposition

which also implies a broad format of solution specification. In automotive design, it was observed that search in the problem space includes two distinct stages of 'exploring the broad format of problem space' and 'problem decomposition' with two separate outputs of 'product brief' and 'product specification' for each stage. However, in the design of less complex products, such as those designed by the case companies, only one document is produced (either a brief or a product specification). In these instances, a broad exploration of the problem space and the problem decomposition stage appear to be fairly interwoven. In other words, in such situations searching the problem space still needs some degree of decomposing the problem, but this is fairly fuzzy and not as distinguishable as the automotive case from other stages of searching the problem space.

Table 6-1 summarises the activities identified in the interviews that are carried out throughout the problem definition stage and coded in a way to reflect similarities or differences with previous cases.

Activities during the problem definition stage	Evidence from the interviews
Users need analysis	"The clients can come with rather variable requirements, they can come and say we have this design, but we have a problem for it to be manufactured, or they may say we want a paint pump designed, and if we ask what spec you want, they say I don't know you are the expert. So, we have to work to develop the spec, see what are the key elements, may be work with the users to understand what the problems are, what the current processes and solutions for painting a wall are and basically define what the user spec is. and from the user spec" (Design engineer, Design Consultancy B, 2014). Looking at the different users' needs, focus groups and things like that, …, what we are doing actually is defining the experience we want to create which then becomes product definitions (creative director, design consultancy A, 2014).
Knowledge pooling & **Problem decomposition (Fuzzy)**	"from the user spec, you define a technical spec and also the industrial design spec and from those two work streams [the final spec is created]. I am not sure if I call them two work-streams though, as we work very closely, and there are a lot of cross-talks there to see if we are on the same ground. … so at this front end, people like A do some usability dig in, human factor side of stuff, and this has really an impact on the direction

Activities during the problem definition stage	Evidence from the interviews
	of spec“ (design engineer, design consultancy B, 2014)
Understanding the completive environment	“I think when we do the final spec, we try to over emphasise there are promotional touch points in that product and then we try to isolate and highlight on it a bit more and strengthen it” (product engineer, design consultancy B, 2014)
Iteration in the problem definition stage (Initial attributes trade-offs)	“making differentiation from other products needs back and forth. So, you may say let’s have a paint pump of this big and the engineers say we need more space. So, we say what can we do, and say we can put in a LED battery, but then say hang on it is too heavy. This type of talk can happen at the early stages, and before we decide the product spec.” (design engineer, design consultancy B, 2014)
Parallel search at the problem definition stage	“We can get like [company X] they will come and say I need a toaster. That is it. And what we had to do, is that we had to go through a process of throwing the net very wide and exploring a whole lot of things, they like to give you a price, they might say I need a 29.99 toaster. And that is often what you get, and then we explore lots of different avenues, put those in front of them and then we propose questions to them, we say ok what is it that you want this toaster to be? And they say Ok we like this one or we like that one or whatever, and then you take that direction …. Often you create the brief for them. Because they don’t understand what they want” (creative director, design consultancy A, 2014) “But to start with, if I go to this one, this is Photoshop rendering, so that we just coloured in Photoshop, and then they [client] say yes that is the direction we want to go... So that was a question that we would define in the brief (creative director, design consultancy A, 2014)
Deciding a broad format for the solution.	“The thing that you do is that you are asking the sorts of visual questions. The visual questions provide the word for the brief. So for example they might say yes, we do want something that has a slightly retro feel, we do want something that is more contemporary, we do want that it is actually plastic or stainless steel, we do want those materials only, you know, we tend to do sketches and then put rendering in front of people, we make them think what is the experience they try to create. With toaster you create an experience, you see, and that is actually now we are going through a process we actually are trying to do.” (creative director, design consultancy A, 2014).

Table 6-1 Activities in the problem definition stage in small domestic appliance design

In addition to the data collected through the interviews, one of the interviewees gave us access, and permission to use a diagram, mapping the different activities they do throughout their design process. This is depicted in Figure 6-1.

As can be seen from the image, activities like a focus group, the user needs analysis, lifestyle scenarios can be considered to all fall part of the stakeholder analysis; while some other activities like branding, benchmarking and associated sector analysis can all be part of examining the competitive market. What is interesting in this image is that it shows that activities like product architecture and experience definition fall on the border of problem definition and solution development stage. This is consistent with the finding of this research, which shows that the output of the problem search stage implies the broad format of the solution space.

Figure 6-1 Different activities conducted throughout a typical design process (Source: creative director, design consultancy A)

8.1.2 The Process of Searching the Solution Space

After re-defining and partitioning the problem space, to the degree that is needed depending on the complexity of the product, the industrial design and the engineering teams start searching for the solution within the defined solution spaces. The process is very collaborative and for both cases that were studied as part of study 3, the

collaboration was closely between two individuals, a mechanical designer and an industrial designer, that were sitting either close to each other in an open-plan office or had day-to-day catch-up.

Due to the size of the product, which ultimately dictated the size of the design team, the collaboration involved a lot of informal conversation and exchange of ideas, making it possible for the design team to get an understanding of their mental models, requirements and considerations without creating a physical medium.

Creative Generation of mental models

Like the other two cases, the creative phase of developing the solution and the first stage of searching the solution space involved creating mental models and the overall design solution.

Within the studied cases, this process started with a brainstorming session, which was described by one of the interviewees as below:

> "I think the initial brainstorm we have like a half day process of all being in the same room, and everybody dumping down their thoughts in the table, with technically how you would operate this machine, and then how that visually impact on the outer skin and how you would use it. So, we all work at the same table. So, you not literally doing a sketch and disappearing off, we all work together, at least you are in a similar mindset … . We also tend to have brainstorms with the client and that will give us a lot of interesting stuff and then we go away and what we have chosen to be the promising directions we then develop and revisit with clients (product engineer, design consultancy B, 2014).

Parallel with the findings of the other two cases on sources of ideas, similar triggers were identified to inspire the designers for deciding on the search starting point and search space boundaries. These are summarised in Table 6-2.

Sources of ideas	Evidence from the interviews
Actual problem and relevant materials designers are supplied with	"There are always touch points and user sides there and then emotional side, you guys tend to talk about feeling, so for a nappy bin, it might be safety, mumsiness, or dadyness, or whatever it is, all those emotional states, you got to put together mood boards, don't you? So you might have for example if it is aggressiveness, you might have a sports car on there or some of those shapes to drive and inspire the sketches and then you kind of do a lot of free sketching, of little bits or overall things and try to develop ideas on would be the key element?" (Product engineer, Design Consultancy B, 2014) "I think that the driver from our very first steps is with the usability and human factors because without those insights you can't really find emotional points of contact" (product engineer, design consultancy B, 2014).
Competitor designs	"We might even draw some kind of a map of the technology space. Actually, if this is where all competitors are at, finding slightly higher than that peak is not very competitive. So, in a way we are kind of mapping these technology space and what we quite often do is to say they have probably done a decent job with that technology, but we need to do better" (product engineer, design Consultancy B, 2014).
Successful examples from non-competitors work"	"but what works and doesn't work form a user interactions point of view is not thinking within a box of the sector…, you might have inspirations that work from a very different sector" (design engineer, design consultancy B, 2014).
Trends in the industry and general market trends	No data from the interviews
Triggers from past experience	"you know from your past experience what works and what doesn't work. …, people who have experience with similar problems give you ideas, so I guess you end up in a room, with a problem, brainstorming how you are going to do it, and no judging in the brainstorming and then afterwards you put your sensible hats on" (design engineer, design consultancy B, 2014).
Combining ideas	"So you end up trying to come up with ideas of decoupling them or um, I mean a bunch of brilliant ideas, there was a lot of whiteboard space covered, and one of our guys just had to sit down and search through the whiteboard, just group them up so really somebody got to sit down and say actually I think these ideas here, I find them very similar, they got common features, so you grouping the ideas… we do that we posted notes a lot…" (design engineer, design consultancy B, 2014).

Sources of ideas	Evidence from the interviews
Inspiration from other sources	"sometimes we may go to universities, look at other literature or competitors' products or products looking at similar problems in different industries. To get all this experience which may be relevant, but which may not be of this territory. And through brainstorming and analysis to say OK where are the fundamentals of this problem (product engineer, design consultancy B, 2014).

Table 6-2 Sources of ideas (search starting points) in the design of small appliances.

Similar strategies for narrowing the search space boundaries were also observed in the designers' approach in the third case, as documented in Table 6-3.

Strategies for narrowing down the search boundaries	Evidence from the interviews
Decide the genre and sort of message to communicate	"you want to have 2 or 3 strong messages you want to convey through your design, you don't look at every feature, you look at the main messages and try to tight them to what the client thinks as well" (creative director, design consultancy A, 2014).
Eliminate	"So, you may have a scoring system to try and narrow down your search, but you got to have experience as a project leader" (design engineer, design consultancy B, 2014). "so we narrow it down before we show it to the client, and then we show it, and we might even say, we think that this one would appeal to this kind of market and in doing that, we are inclined to determine what we want and if we have done our job well enough then we would cover a sector where his target or his target market would sit within. So, and then they narrow it down to maybe two or three directions which we then do the final details on them" (creative director, design consultancy A, 2014). "One thing might be it is a saturated area. we have a bunch of ideas and actually all these ideas at the very beginning you may do a concept screening, and that rely on some understanding of the landscape" (product engineer, design consultancy B, 2014).
Change perspective	"you classify those groups to maybe five or six ideas, then you can get them all on one page, and then as a group maybe with a client maybe with experts … you look at them and go well actually is there any physical, engineering or design reason that this can't work, so you can kind of screen out the ones which aren't going to work" (design engineer, design consultancy B, 2014).

Strategies for narrowing down the search boundaries	Evidence from the interviews
Define rules	"We say OK what are the things that are important from a really top-level spec, so things like development cost, manufacturing cost, compatibility with existing manufacturing systems, user delight or something like that and performance, you might then say well each of these actually which of these are more important, maybe rate those" (design engineer, design consultancy B, 2014).
Name potential areas	No data from the interviews

Table 6-3 Strategies for narrowing down the search boundaries in the design of small appliances.

As can be seen from this data, the strategies for identifying the 'search starting points' and 'search space boundaries' that contribute to the offline phase of the search closely resemble those used in the previous two cases. The only difference, once again, lies in the presence of multiple individuals involved in designing the product. In this context, a physical medium becomes necessary to communicate the mental models among members of the design team. Brainstorming sessions and the exchange of opinions and ideas between designers and engineers play a pivotal role in the offline search for design of household appliances, which serve as examples of products with medium-level complexity.

6.2. A Framework to Describe Search Process in Design of Small Appliances

As was observed and explained in the previous section, in the design of such a medium-complex product searching the problem space still needs some degree of decomposing the problem, however, due to the close collaboration of designers and engineers and the small size of the design and engineering team (which by itself is dictated by the complexity of the product), this decomposition is fairly fuzzy and not as distinguishable as the case of automotive design. Accordingly, the decomposition of the solution space is not present as such in this case. This vague and loose form of decomposition and the associated close collaboration is evidenced further by the quote below:

> "Even as sketches are developing, we will review it together and I say do you have to have a button over there because it is awkward (just by experience) and he says no it is important because of this

> and this. So, there are internal reviews and discussions all the time" (design engineer, design consultancy B, 2014).

The experimental part of the search is comparable with what was observed in automotive design, with one key difference: there is no need for an arbiter in such cases, as communications that are required for adaptive moves can happen directly between the agents. This is further explained by one of the interviewees below:

> "So, you have a work-like and a look-like and for the look-like model might be a physical 3D model with no functionality, this is here is the look and feel, here is the colour, here is the tough points, you can imagine lifting this, and you can imagine pressing this button. so, the client gets to see here how it is going to look like, but not how it is going to work because from a technical point of view just too much work is needed to get to a look-like and a work-like model in step one. And in the next step after this is essentially the look-like work-like model, so from here on in you are developing towards something which is manufacturable and we work much closer together when fulfilling function" (design engineer, design consultancy B, 2014).

The variation and selection stages are again through generations of physical models and selecting the most promising ones:

> "And actually, in a more complex product, you may have many more models, so the more complex things are the more you ought to make the models along the way to keep bringing uncertainty down as your exposure does increase" (design engineer, design consultancy B, 2014).

To generate such models, designers and engineers work closely together and adapt their solutions to reach a mutually agreed optimum.

> "Then you are developing sketch principles around an envelope and then the technical team developing within the envelope" (design engineer, design consultancy B, 2014).

One other key difference that was observed was the lack of 'adaptive mutation': the introduction of new technologies to change the landscape when there is a strong desire to achieve higher performance. However, this can be related to the limitation of this study as the products that were designed by the case companies were not highly novel and disruptive. However, due to a lack of evidence to support the existence of such a step in designing medium-complex products of the types that were studied as part of case study 3, the adaptive mutation step is not present in Figure 6-2 Search process in small domestic appliance design.

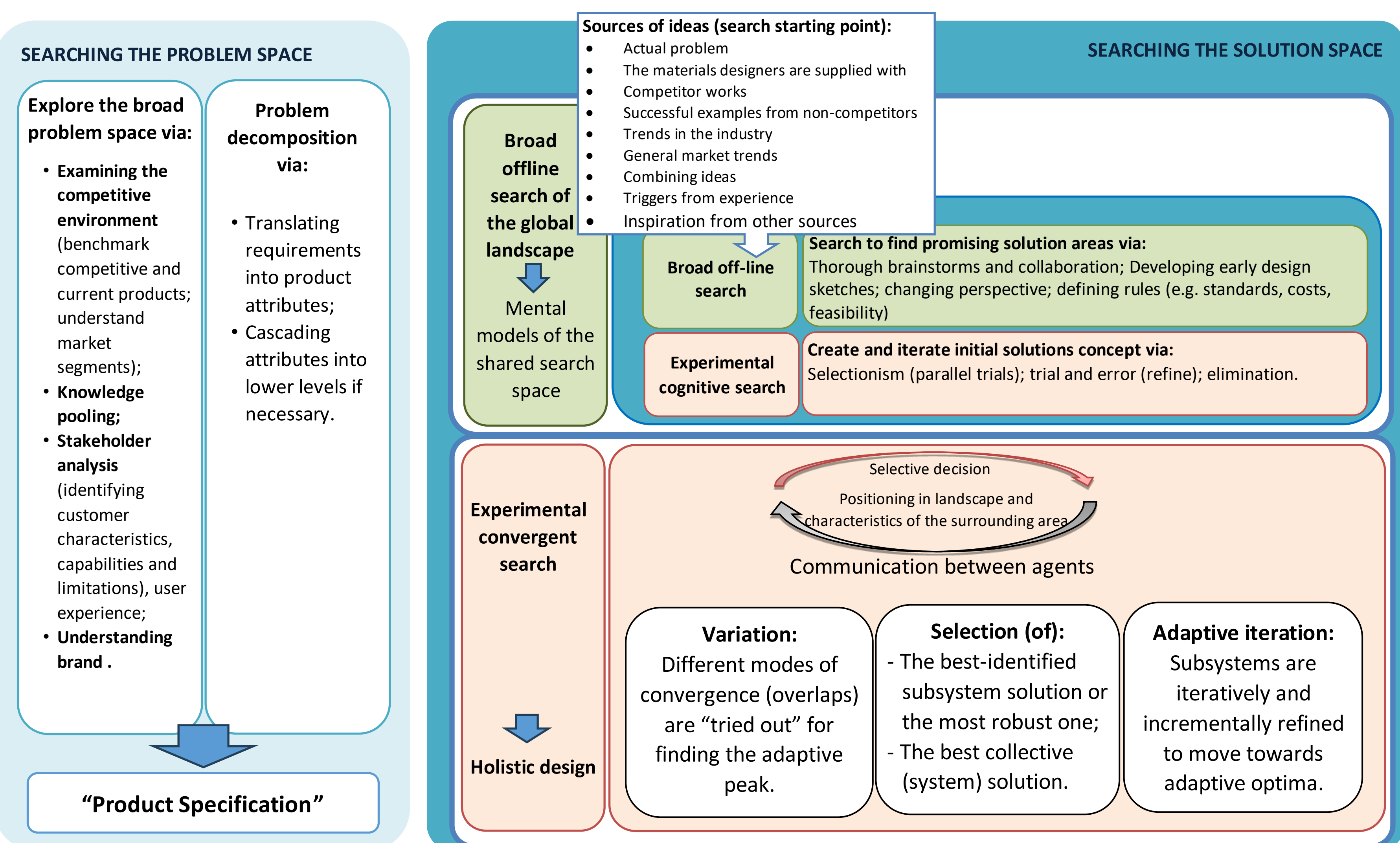

Figure 6-2 Search process in small domestic appliance design

As previously outlined in the data collection section, this study meticulously selected cases across a spectrum of design projects characterized by varying levels of holistic complexity, as elaborated in section 2.7 (Holistic Design). This approach yielded case study results that provided detailed descriptions of the design processes and their distinct characteristics within each sector, which were then articulated through conceptual frameworks. This methodology directly addresses Research Objective 3 (RO3), which aims to explore the design process from a search perspective in practical settings and articulate the findings through conceptual frameworks. To fulfil the remaining research objectives and address the second research question, an analytical comparison and contrast of the cases and their respective frameworks were undertaken to discern similarities and differences among them. Chapter 7 delves into the comprehensive findings and analyses that contribute towards achieving the thesis objectives.

7. Findings and Analysis

The thesis so far described the observation made and preliminary analysis of the findings from the case studies and has examined how designers approach holistic design problems in three cases (graphical design, automotive design, and household appliance design) that differ markedly in their complexity. The developed conceptual framework provides a rich insight into similarities and differences between the search processes in the design of products which differ remarkably in their complexity. Similarities can be observed in the identification and understanding of the problem space. In all cases, this understanding requires close collaboration between designers and customers. As well as identification of and discussion with different stakeholders of a business. In the more complex vehicle design case, searching the problem space involves an additional stage of problem decomposition, which also implies the construction of a hierarchical structure for the solution space, while for the case of small household appliances the decomposition is fairly fuzzy.

It was also examined how designers search the solution space. This step leads to the identification of a solution space which prompts the finding of solutions through the general manifestations of initial ideas. Here, similarities between cases can be observed in the creative part of search, where broad solution characterisations and search starting points are identified. This is done through creative and then eliminative development of mental models. Sources of ideas identified in the findings include the actual problem and relevant materials designers are supplied with, competitor designs, successful examples from non-competitors, trends in the industry, combining ideas, triggers from past experiences, and inspiration from other sources. The identified strategies for narrowing down of search boundaries include the decision of the genre and sort of message to communicate, elimination, perspective-changing, rules definition, and the mentioning of potential areas. In designing a complex product, teams need to find a medium for communicating their respective mental models to one another. This means that they need to produce "physical outputs", such as sketches, 3D models or clay models. Thus, experimental search at the subsystem level starts from the offline search stage at the holistic design level.

Furthermore, it was examined how designers (experimentally) explore the global solution space. Here, the processes differ significantly between cases, even though the search

activities in all cases involve the two fundamental building blocks of trial-and-error learning (i.e., refining the solution with the emergence of new information) and selectionism (i.e., running multiple parallel trials and choosing the best option). The more complex the product, the more need for formal and frequent communication and coordination. As was observed in the automotive design, the complexity required diligent coordination among teams that search subspaces. The role of a coordinator (the attribute team in the automotive firm) is therefore key in achieving a high-performance whole out of parts. Designing a complex product also requires teams to continually communicate information about their respective search space and local optima and to receive information related to other teams' as well as guidelines for adaptation. This continuous dialogue and adaptation are other characteristics of search approaches in designing complex products.

Furthermore, the results can also be analysed using the concepts from Kauffman's NK model (as discussed in 2.9), where N is the system size and, the K value defines by how many elements each element in a system is affected. Thus, the value of K can range from 0 to N-1, and the bigger it is, the more rugged the fitness landscape would be. The search landscape for all cases is rugged, this is because by definition, for holistic design K takes the closest value to N. However, as the complexity grows by system size, the number of peaks in the landscape increases exponentially. Hence, partitioning (decomposition) of the landscape is needed as not only the search agent (human) can only search a limited number of variables (due to bounded rationality) but also the number of peaks increases which means that there are many more candidate solutions available. The decomposition implies a need for communication, coordination, and comprises to be made. Also, with an increase in the system size of the holistic design, and the subsequent decomposition of the solution space the number of local optima increases so as opportunities to arrive at a better solution. However, the search process becomes more difficult and uncertain, as there are more interdependencies to manage. Also, a local search will be less effective and most possibly lead to a local optima rather than global optima. So a wider search is required but in effect, in the design of very large complex products like a new vehicle the design team don't perform a very wide search, instead engineers spend their time trying to predict, avoid, and debug the subtle interactions between components, rather than exploring new combinations, and although the process starts with styling (which is more creative) to widen up the search scope; the

narrowing down process happens very quickly and conservatively. Also, in Kauffman's metaphorical landscapes, agents can move beyond simple search patterns. The searching agents and the action of search can change the landscape intentionally (by introducing new technologies or components) and unintentionally (by moves that result in change propagation). The landscape is hence dynamic. Therefore, the aim of search at subsystem levels is not only just to find optimal solutions, but also to continuously adapt the solutions to a changing environment and to change the environment where necessary. Once a holistic solution has been achieved, each team can still perform a local search (within the constraints of not affecting the other teams) to fine-tune its own sub-system solution as seen in the case of automotive design.

The contributions of the frameworks are of two folds: First, the models enable analysis and representation of the design process through a search perspective. In doing so not only do the models provide practitioners and academics with rich insights into the design process and empower them with a better understanding of the process, but also, they capture certain characteristics of the design search that were absent from major models of design as discussed in chapter 2. Table 7-1 represent examples of capturing characteristics of the design process through the frameworks.

Intuitive/ Creative	Iterative	Concurrent	Co-Evolutionary	Risky	Collaborative/ Social	Complex and Hierarchical
Creative Generation of mental models. **Idea generation to define the search starting points.**	Trial and Error in Experimental part of search. Local search to fine-tune the final sub-system solutions.	Exploration of various routes. Parallel search in sub-solution spaces.	Coevolution of sub-solution spaces and sharing of the information.	The change of landscape is managed through adaptive convergence and adaptive mutation.	Knowledge pooling and stakeholder engagement in the problem definition stage. Communication between agents and the need for an arbiter in the solution space search.	decomposition of the problem and solution spaces.

Table 7-1 Examples of representation of characteristics of the design process in search-based models of the design process

The frameworks also characterised the search activities in holistic design in cases with dissimilar complexity. Drawing on the insights from Table 2-3 Audiences for design process modelling (O'Donovan et *al.,* 2003)), this study offers managers detailed guidance on selecting the appropriate processes, resources, and tools essential for the development of products across varying complexity levels.

Reflecting on the empirical findings in conjunction with the literature review presented in Chapter 2, this study critically addresses Research Objective 4. The literature highlighted limitations in existing design process models, particularly in capturing the subtle characteristics of design search. In contrast, the empirical insights from this study offer a fresh perspective on the design process, through investigating it via a 'design as search' lens. This comprehensive analysis not only bridges identified gaps in the literature but also identifies critical gaps in understanding the design process across varying complexities, and the implications of that in key characteristics of the design process including iteration, concurrency, and coevolution. The analysis of empirical findings thus far imply that complexity is a critical factor influencing the design search process, hereby addressing Research Objective 5. Building on this, the subsequent section will not only provide further elaboration on Research Objective 5 but will also delve into Research Objective 6. By doing so, the analysis aims to effectively address Research Question 2 and achieve its related objectives.

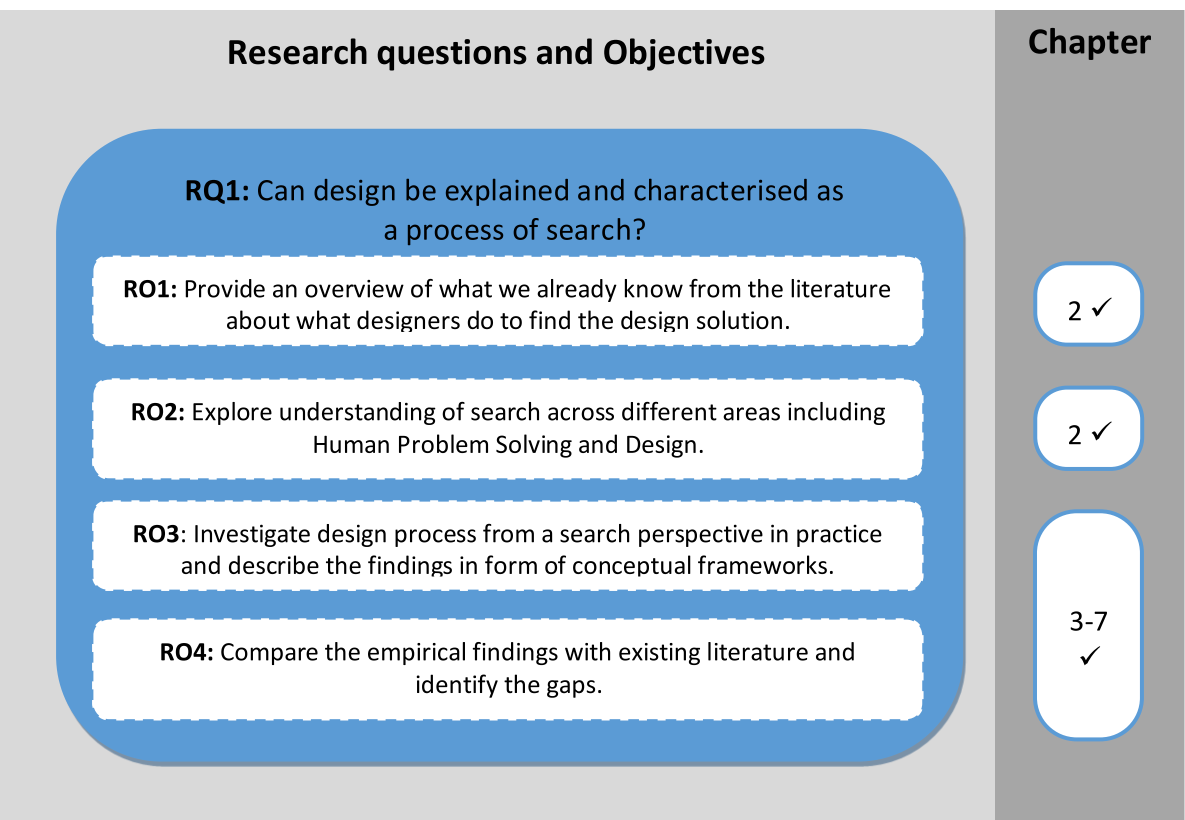

Figure 7-1 Research question 1 and subsequent objective

7.1. Identification of the Influencing Factor

Chapter 2 (section 2.7) provides a definition of the holistic design as it is applied within this thesis:

> *"holistic design" view the design solution as an interconnected and integrated whole, where its performance is the result of nontrivial and complex interactions among multiple parameters and components.*

It was mentioned that this conception of design is marked by several defining characteristics:

- **Indescribable Overall Performance Function:** The collective performance of these designs eludes precise mathematical expression, reflecting the intricate and multifaceted nature of how different elements contribute to the final product.
- **Contextual Significance of Component Performance**: The performance of any single component gains meaning only within the totality of the product, underscoring the interconnectedness of all parts.

- **Interdependent Component Characteristics**: Each component's effectiveness is closely tied to the characteristics of other components in the system, highlighting the need for a holistic approach to design where every element is considered in relation to the whole.
- **Complex Customer Preference Dynamics**: Customer preferences emerge from a complex interplay of performance parameters, indicating that attractiveness and desirability of the product stem from more than just its functional capabilities.
- **Subjective and Emotive Customer Evaluation**: Preference and product valuation are significantly influenced by subjective and emotive evaluations, suggesting that effective design addresses both the analytical and emotional needs of users.
- **Multiplicity of Design Parameters**: Holistic design acknowledges that each component is characterized by numerous design parameters. Optimal product performance is achieved through the careful adjustment of these parameters, often requiring a nuanced and iterative approach to design refinement.

In addition, the thesis also reviews Kauffman's NK Model, in which 'N' represents the number of elements in a system, and 'K' determines the number of elements each component is influenced by. Therefore, 'K' can vary from 0 (where elements are not interlinked and the system's complexity is minimal) to N-1 (where every element is interconnected, resulting in maximum complexity). Systems characterized by holistic designs usually exhibit a high degree of interaction among elements, implying that 'K' often assumes higher values. For simplification, it can be assumed that 'K' equals N-1 in holistic designs.

This assumption leads to the conclusion that the complexity of a holistic design changes with the size of the system, 'N'. That is, the larger the system, the greater its holistic complexity. Essentially, holistic systems represent a category of complex systems where complexity is directly influenced by system size.

To further illuminate this analysis, another framework, the concept of "product architecture" from Ulrich and Eppinger (1999), is introduced. Product Architecture "mean the scheme by which the function of a product is allocated to physical components of the system, and by which these components are arranged" (Ulrich 1995). they distinguish between modular and integral architecture where for:

Modular architectures: "the mapping from functional elements to components is one-to-one, and the interfaces between components are decoupled". Hence, a modular design is not complex nor holistic.

Integral architectures: "the mapping from functional elements to components is complex and/or the interfaces between components are coupled".

By distinguishing between modular and integral architectures, Ulrich and Eppinger provide a lens through which the complexity and holisticness of designs can be examined. Modular architectures typically results in products that are less complex and less holistic, as changes in one component do not significantly affect others. In contrast, integral architectures are more holistic design for which the intricate interdependencies must be managed effectively.

These frameworks assist in analysing the case study products, categorising them based on their architectural attributes and, consequently, their relative complexity and holistic quality. Table 7-1 organises products along two dimensions: 'Complexity', as defined through the NK model discussion, and 'Holisticness', i.e. holistic quality, determined by the degree of interdependency among component parameters.

The table arranges products in descending order of complexity in Column A and ascending order of holistic quality in Column B. This table underscores that while complexity and holistic design are interrelated, they do not always directly correlate; some less complex projects can still exhibit significant holistic qualities depending on the depth of design considerations.

For example, 'White Space Car' projects, exemplifying integral architectures, are marked by high complexity and holistic quality due to their extensive system size and the deep interdependencies among components. In contrast, car update projects, focusing on targeted changes without affecting other car aspects, exhibit decoupled interfaces and less complex mappings from functional elements to components. However, some degree of iteration is needed to integrate these components properly.

Reviewing product architecture shows that products from consumer design case, though mid-complexity, are the least holistic as their mapping from functional elements to

components is not complex. Graphic design products, while not complex, are fairly holistic due to their coupled interfaces.

This comprehensive approach, incorporating both the NK model and Ulrich and Eppinger's product architecture concepts, provides a detailed understanding of the interplay between complexity and holistic design within the case studies, presented succinctly in Table 7-1 and visually represented in Figure 7-2.

Complexity (derived by system size)	**Holisticness (Degree of holistic quality)** (derived by overall performance function being governed by the degree of the interdependency of component parameters)
White space car	White space car
Car update	Advertising video- Logo-Poster- direct mail (graphic design)
Advertising video (music + content + image)	Car Update
Paint pump	Paint pump- Nappy Bin
Nappy Bin	Kettle-Toaster redesign
Logo-Direct mail- Poster (typical graphic design)	
Kettle, toaster redesign	

Table 7-2 Example products from the data set reordered based on their complexity and holisticness

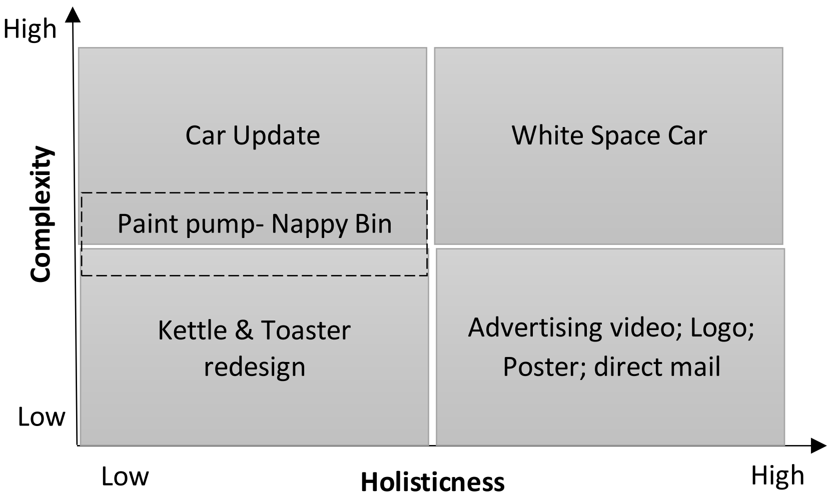

Figure 7-2 Example products from data set reordered in Complexity-Holisticness matrix

Furthermore, from this analysis, it can be concluded that holistic architecture is a specific form of complex (integral) architecture, with complex mappings and coupled interfaces necessitating a careful search to define and refine these interfaces. Variation is also essential to gauge customer subjective responses effectively. As one of the interviewees noted, in car

design, aiming to create and develop a new concept involves initiating the process by requesting 3-5 designs from each designer. In contrast, projects focused on redesigning an existing car typically require only one design per designer.

Research Question 2 aimed to uncover characteristics that systematically affect the nature of design search. The analysis presented thus far demonstrates that complexity significantly influences the search process for holistic design, thereby addressing Research Objective 5 (as illustrated in Figure 7-3). Moving forward, the analysis will look into the various stages of the design search, as observed through empirical findings, and undertake a comparative examination of these processes across different cases, with complexity serving as the contingency factor.

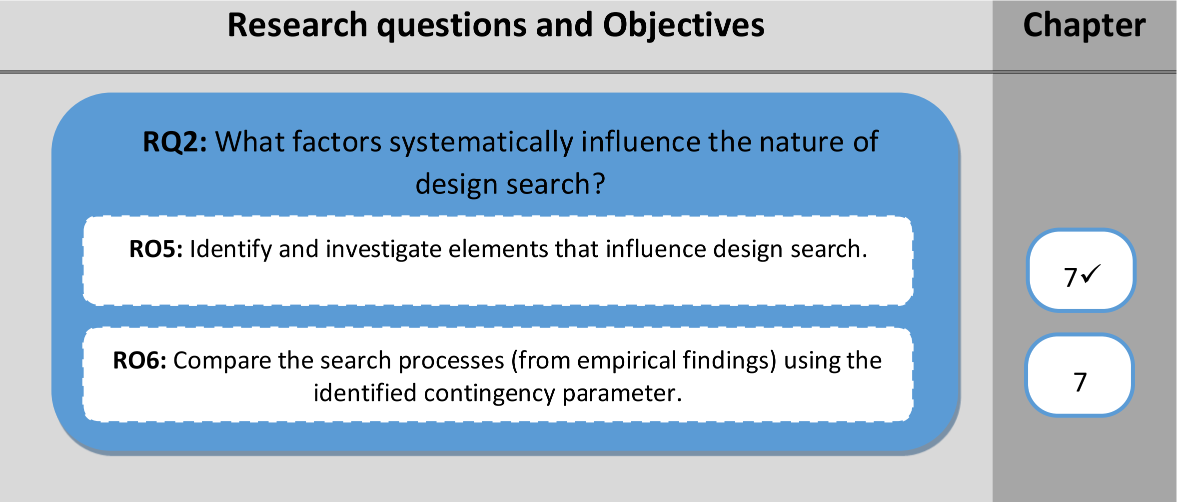

Figure 7-3 Outline of the second research question and subsequent objectives and the current state of the thesis

7.2. Further Discussion and Implications

To systematically compare the developed frameworks and achieve Research Objective 6, the analysis contrasts the design search stages for both high and low-complexity holistic designs against those for high and low-complexity modular designs, which exhibit lower holistic qualities. This comparison is presented in Table 7-3 for holistic designs and Table 7-4 for modular or less holistic designs, drawing upon insights from the interview data.

	Reframing the problem	De-composing the problem	De-composing solution space (Parallel search in individual landscapes)	Broad off-line search (to find the search starting point and boundary of the search landscape)	Feedback loop to problem definition stage (revisiting problem after an offline search)	Initial/high-level experimental search (for communicating mental models, creating and exploring interdependencies) broad co-understanding of search landscape)	Variation in the experimental search stage	The need for an arbiter	Adaptive iteration	Adaptive Mutation	Timing	No of teams involved
Holistic/ High Complexity (e.g. White Space Car)	Marketing identifies the need, and a multidisciplinary team including market researchers, designers, engineers and researchers develop the "product brief or a-ssumptions".	Critical "attributes", the architecture of functions and performance requirements are defined as: "Product specification".	Multiple teams search subspaces: e.g., packaging, exterior, Body engineering chassis ….	Sources of ideas: existing products, trends in the market, etc are reviewed and Initial constraints are set through feasibility discussion, legislative requirements, and Senior managers' input ….	Possible before design freeze stage, but very limited (product specification might change but not product brief).	e.g., computer modelling is used to merge sketches with 3D package data. Two or three virtual models get turned into clay models.	2-3 clays: One or two concepts are picked to work with and the process is opened up again with more designers to redraw some more details around it, then these are iteratively refined to come down to e.g. sort of headlamp and grill in more themes and that will form the 'go for one design which is then progressed with much more details with the engineering team.	attribute team decides which performance requirement is more important.	Controlled and guided to find trade-offs, as well as to improve individual solutions: clay models are tweaked and iteratively refined and different lines in the vehicle are tried out.	design group might come up with interesting visual designs some elements of which need to be achieved through the generation of new technology.	Months for planning, years for execution "For a full vehicle program, we take around 4 years. We do what we call 'Stop Clay' and from the beginning to that point will be around one year and a half. the planning of how to search the identified problem and solution. spaces take six to twelve months, a time frame that is so long that the attributes and performance requirements may not remain constant.	Multiple teams – coordinated by arbiter.
Holistic/ Low Complexity (e.g. Graphic design project: e.g. direct mail, advertising campaign)	"Once the diagnosis we go back to the business and we say actually we think this is the problem we solving and not the problem you gave us"	**NA** due to the small system size and low complexity	**NA** as the problem is not decomposed	Ideating and narrowing down happens: "then we are down to kind of expression, and that leads to what the detailed format and shape would be, then we are almost to production. So, there is a process before the design process and there is a whole process that kicks in just around production and graphics kicks in at that point.	Possible: "We told them with more budget, we could have more involvement, so it would be three people working on this, we could look at what their motivation was for people for getting these calendars".	Computer models and presentations, mainly to communicate ideas with clients: "We have to be able to communicate…. We actually, call each of our possible designs by a name. So, we call these the roots, actually in that initial concept presentation, we had three roots … so we named the roots, it helps the client as well it is another kind of boundary or sort of circling the information".	Many times we try to offer three roots. actually, it was in the initial concept presentation we had three roots, and they were, the magnetic root, the optical root and the before and after root.	**NA** due to the small system size which only requires a single designer or a very small team to work on the product.	We create something and then we rework it until it satisfies the customer. It is collaboration, and therefore their input is required in order to make the whole solution. so perhaps you need to try these things and say OK it doesn't give me a pleasing feeling, so trial and error.	**NA** the landscape is not usually that dynamic to require adaptive mutation.	Weeks for planning, months for execution. When we received the questionnaire, we will meet the client in a week or two and discuss what the project might look like.	Single team.

Table 7-3 Comparison of the search process for low complexity and high complexity holistic design

	Reframing the problem	De-composing the problem	De-composing solution space (Parallel search in individual landscapes)	Broad off-line search (to find the search starting point and boundary of search landscape)	Feedback loop to problem definition stage (revisiting problem after the offline search)	Initial/high-level experimental search (for communicating mental models, creating, and exploring interdependencies) broad co-understanding of search landscape)	Variation in the experimental search stage	The need for an arbiter	Adaptive iteration	Adaptive Mutation	Timing	No of teams involved
Low holistic/ Medium Complexity (e.g., car update)	The brief is already tight, and the system constraint is very clear.	The problem is already decomposed in the system level. The project specification describes how the proposed change needs to fit within existing constraint.	Few teams can be involved in searching individual spaces, with defined boundaries: e.g., stylist to redesign the bumper to give the car a more contemporary look	Ideating and narrowing down happens, but much less in comparison with the holistic design. Fewer variations. Boundaries are also mainly known so the search is mainly to find the peak rather than finding the starting point and boundaries: If we redo the ford, we may just ask a few designers to give us one design each.	It might be the case that the new feature is so attractive that three maybe need to change in another element of the car, this is very rare to happen	Computer models are still used	Limited	**NA** The constraint is already defined, and there is no need for trade-offs	Not to find trade-offs, but to find the best fit	**NA** Fairly low-risk projects – The aim of the project is not to introduce a breakthrough tec but to upgrade an existing subsection	Information was not captured in the interview	Single team
Low- Holistic/ Low Complexity (e.g., redesign a kettle feel to make it more contemporary)	Some designers work with tight briefs. The customer comes with a defined need. Normally these projects are delivered with minimum tight and budget	N**A** due to the size	The engineering constraint is defined, generally, there is no need for much involvement from them. This can be a purely artistic project.	Ideating and narrowing down happens, but much less in comparison with the holistic design. Fewer variations.; Boundaries are also mainly known so the search is mainly to find the peak rather than finding the starting point and boundaries. I told them I have something from a past client that we might be able to use.	Not common	Computer models	Limited	**NA** The project is usually conducted by one designer	Within the project constraint, to find a solution that satisfies the client	**NA**	Information was not captured in the interview	Individual designer

Table 7-4 Comparison of the search process for low holistic design with different degrees of complexity

The above analysis further highlights the similarities and differences between the search processes in these cases. From the analysis, it can be concluded that the complexity and holisticness of the design dictate certain search strategies throughout the design process. Analogous to the Complexity/Holisticness grid as presented in Figure 7-2, Figure 7-4 maps the search strategies employed for the design of products according to the degree of complexity and holisticness of the design. The vertical axis represents low and high complexity. The horizontal axis represents a measure of “more" or "less" holistic design.

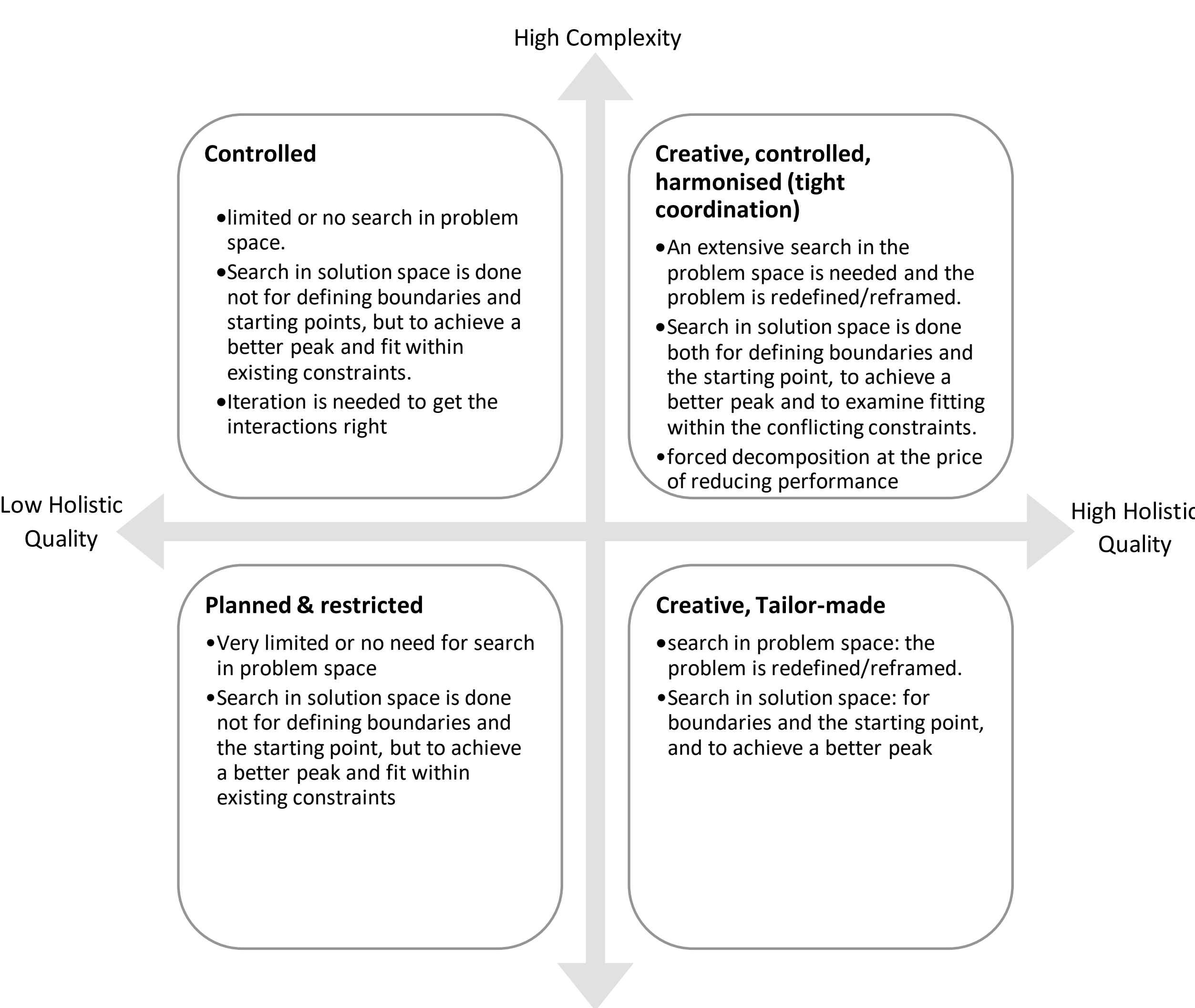

Figure 7-4 Search strategies for coping with the complexity and holisticness of the design

The strategies listed in the diagram are further elaborated below:

Planned and restricted

The typical characteristics of such projects are tight briefs, limited budget and short time scale. In such situations, designers are dealing with an isolated, rather well-defined design problem. As the project scope is well defined, search in the problem space is very limited or not needed. The design problem in such cases imposes no holistic complexity. So, for example, in the redesign of a kettle, the function will be untouched and only the form of the product needs updating; hence, there is no need for coevolution of the form and function, which is one important characteristic of holistic design. A very small team or even one single designer conducts the project; therefore, communication between search agents is not needed or is done rather informally. The nature of the project implies a search within already defined boundaries, and due to the limited budget and time frame of the project, ideating (search for the starting point) is also limited. Using off-the-shelf designs or reusing an idea from previous designs is not uncommon. As the purpose of such projects is usually a minor upgrade of the product, the purpose of search and iteration and parallelism in solution space is not for identifying the solution landscape, but to achieve a better pick within the known landscape. It is easy to plan the restricted search in such scenarios.

Controlled

The typical characteristics of such projects are again tight briefs and clarity over the system constraint. The Problem in such cases is already decomposed at the system level. The complexity is derived by system size. These projects are fairly low-risk projects as the aim of the project is not to introduce a breakthrough solution but to upgrade an existing solution at the sub-system level. Referring back to the discussion about the feasibility and holistic complexity in section 2.7 the project mainly aims to improve one attribute and performance, in the end, is driven by this attribute which by itself can be influenced by all the other attributes due to the system being complex. Hence, controlling factors of the performance can be reduced to getting that attribute right. However, to control the influences of other attributes, the project is well-defined and describe how the proposed change need to fit within existing constraint. The project team also must implement rigid control over local tweaks to the design to keep the boundaries of a known control state and to avoid the need for any trade-off or any change propagation.

Creative, Tailor-made

These projects are usually characterised by an open brief where the budget and schedule might be subject to review before starting an on-line search of the solution space. As well as the solution space, the problem space needs to be reasonably searched with input from the client and through strategies marked in Figure 4-1. Iteration and parallel trials are required to identify and define the problem and the broad format of the solution space. More ideas might also be explored at the offline search stage. Iteration and parallelism in solution space serve two purposes: to know the landscape better and to achieve a better performance peak pick within the known landscape. The process is a very creative process and ideating, and different methodologies to stimulate creative thinking and ideation are used at this stage. Due to a small system size usually a single designer or a small team work on the project which enables informal but constant communication between agents. The design team, however, work closely with clients and rely on their input and localised knowledge to build a fit-for-purpose product.

Creative, controlled, harmonised

Typically, the projects start with open briefs allowing maximum creativity at the outset of the project; however, constraints are added as early as possible to control uncertainties arising from the complexity of the system. Hence, feasibility checks and formal planning and meetings kick in from an early stage and are more formal. Introducing the constraints implies defining the boundaries of the search spaces to enable the feasibility of a complex system design within the available time and resources. Search in problem space typically includes two distinct stages of 'exploring the broad format of problem space' and 'problem decomposition' with two separate outputs of 'product brief' and 'product specification' for each stage. The formulation of the design problem at a decomposed structure is a system engineering approach, which along with strategies such as target cascading, frequent validation points, formal communications and managing interdependencies are used to control search in the rugged and dynamic landscape. The solution space is also decomposed as a consequence of the decomposition of the problem space. Iteration is needed at the offline search and online search stages not only to manage interdependencies and refinement of the subsystem solutions but also to manage uncertainty. The systems-driven approach to the design of

complex holistic products brings all aspects of the design together in a holistic fashion and makes it easier to meet complex and conflicting requirements throughout the design process with regular validation. High complexity requires tight coordination and frequent communication to harmonize the activities of the different teams that are responsible for many interacting sub-projects and fast exchange of information. Hence, the search in such projects needs to be controlled and harmonised while enabling maximum creativity at the outset of the project.

The discussion of this chapter has tackled addressing the objectives of the second main research question as shown in Figure 7-5. The next chapter provides an evaluation of the research and its success and limitations in contributing to its aim.

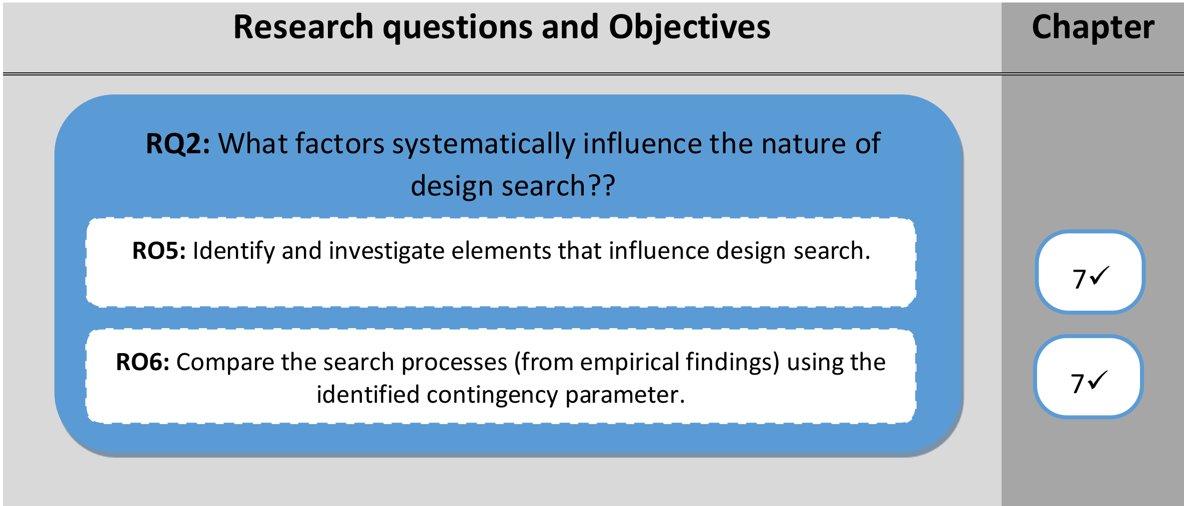

Figure 7-5 Outline of the second research question and subsequent objectives and the current state of the thesis

8. Evaluation, Contributions and Future Works

Considering the discussion in previous chapters, this chapter summarises the key contributions of this study. The chapter continues by proposing areas for future research that build upon the work conducted here. The thesis is concluded by providing a final summary.

8.1. Assessment of Answering Research Questions

The purpose of this study was to characterise and explain the 'search' process and the designer's behaviour in solving 'holistic' design problems that have diverse degrees of complexity. The scope of the study was narrowed to three streams of literature – the design process, the complexity theory, and the search in human problem solving. The research was guided by two main research questions. The success of the research in addressing these research questions and subsequent objectives is discussed below.

8.1.1 RQ1: How Can We and Characterise Design as a Search Process?

This question was instrumental in the evaluation of the first hypothesis that design is a type of search. Also, RQ1 enabled the formulation of the first four research objectives, which entailed offering an overview of what has already been studied regarding what designers do to find solutions to design problems, exploring the understanding of search across various areas, investigating the design process from a search perspective and identify gaps in the literature. These four research objectives were instrumental to the study in the following ways:

RO1- Provide an overview of what we already know from the literature about what designers do to find the design solution.

Fulfilment of this research objective required establishing a systematic understanding of the existing definitions, theories, and models of the design process. For this purpose, the study conducted a review of the current literature in chapter 2 and as the first step identified a wide array of definitions of design, each developed from a certain perspective to design. This step enabled the researcher to learn about the diverse outlooks on the design process and to decide on the direction of the study by blending ideas from relevant definitions to come up with a definition highlighting the focus of the study: "Creation of solutions to problems which

are functional and aesthetically pleasing”. The process is a human problem-solving activity (and hence a cognitive action) with the aim to create satisfactory form and function in a unified artefact.

The dominant characteristics of the design process identified in the literature were also reviewed in section 2.2 and grouped into eight categories, which were later used to analyse a series of theories and models of the design.

Numerous prevailing models and theories of the design process were reviewed to help the researcher to better understand the design process. In order to contribute to the literature and help the research to develop a better understanding of them, the thesis analysed the theories and models in many ways:

- The difference between models and theories was discussed and clarified, as it appeared that the design community use the two terms interchangeably, whereas in some other disciplines like operation management, each term conveys its own meaning. Using the distinctive characteristics between models and theories as shown in Table 2-2, the thesis then classified the perused with the review under two separate headings of models of the design (section 2.5) and theories of the design (section 2.6).
- In addition, a framework is presented in section 2.2.8 which provides an aggregated representation of different classifications of design process models (Figure 2-6 An aggregated representation of the different classifications of design process models). By gathering and representing diverse viewpoints within a unified structure for classifying models, the aggregated framework not only directs the thesis's focus towards qualitative process models but also offers a comprehensive view on design models, assisting researchers and practitioners in making more informed choices for their work.
- Characteristics of the reviewed models and theories of the design were also played against the list of dominant characteristics of design as compiled in section 2.2. Two comparative tables then were developed to articulate the key characteristics of the dominant models and theories of the design: Table 2-7 A comparison of reviewed models of design) and Table 2-9 A comparison of theories of design). This step was

instrumental to fulfilling RO1, as not only it enabled broadening the understanding of the design process that was built in the earlier stage, but also the construction of frameworks for analysing theories and models of design and examining their efficiency and inclusiveness in illuminating the design process. The tables can also guide design researchers by gathering in-depth insights into important aspects of the theories and models of design.

The review of various design models and theories highlighted that while many models capture the complexities involved in the solution development phase, they often overlook the intricacies of problem definition and the exploration it requires. Furthermore, while design is described through lenses such as problem-solving, decision-making, and reflective practices, criticisms arise from the unrealistic assumption of pre-existing topological spaces, undermining the applicability of existing theories in capturing the full essence of design. Additionally, the limited consideration of social interactions and creativity in these theories was noted, underlining their insufficiency in fully encompassing the multifaceted nature of design processes.

In summary, Chapter 2 not only fulfils Research Objectives 1 through a thorough review of literature but also enhances the body of knowledge with the introduction of three informative conceptual frameworks. These frameworks not only lay the groundwork for understanding current design processes and methodologies but also point out the limitations of existing models and theories. This, in turn, prompts the design community to develop more comprehensive, inclusive, and adaptable approaches, and utilising the existing models with full awareness of their limitations.

RO2- Explore understanding of search across different areas including Human Problem Solving and Design.

This research objective helped in the realisation of the aim of the thesis, which was to characterise and explain the search process involved in solving 'holistic' design problems. The literature review underscored that human problem-solving predominantly relies on heuristic methods and satisficing strategies, highlighting the essential roles of abstraction and representation in problem comprehension and resolution.

Discussions on bounded rationality revealed its impact on decision-making, limiting the visibility of all alternatives and their outcomes, thus necessitating the reliance on heuristic approaches and a satisficing rather than optimising strategy.

Further exploration into cognitive problem-solving introduced the concepts of offline and online search (from Gavetti & Levinthal, 2000). The former involves constructing simplified cognitive representations to manage the complexity of various relationships, acting as an abstraction of reality and serving for forward-looking evaluations. The latter, or online search, depends on experiential learning and is inherently limited by the finite nature of personal experiences compared to the vastness of possible actions. This distinction was elaborated through insights from Ulrich (2011) and Darke (1979), pointing out the use of sketches and other representations by designers to reduce cognitive complexity of the design space as well as to record design alternatives in external memory.

It was also noted that four search strategies were highlighted in the design literature by Ulrich (2011) to help designers to manage the complexity of search: hierarchical decisions, parallel exploration and selection, causal relationships, and existing solutions. Further analysis, as detailed in section 2.8, reveals that causal relationships and existing solutions essentially set the search's starting point and narrow down the space rather than direct exploration. It's noteworthy that the concept of schema activation, as discussed by Hey *et al.* (2017), closely relates to and informs these strategies, particularly existing solutions and causal relationships, by providing a cognitive framework for understanding and organizing information. Pich *et al.* (2002) have shown that fundamentally, the search space is explored through two primary strategies: serial search (trial and error learning) and selectionism (parallel trials), or their combination.

In summary, the comprehensive review in Chapter 2 confirmed that the design process inherently includes a human search component, manifested through both serial and parallel exploration of solution spaces. While certain methods identified in literature aim to refine or define these spaces, key elements such as heuristics, schema activation, bounded rationality, satisficing, abstraction, and representations are fundamental in this process. However, there remains a notable debate regarding the integration of creativity, knowledge creation, and social interactions within a search framework, as well as the role of search in problem

definition, indicating areas for further academic exploration and consensus building. This investigation effectively fulfils Research Objective 2, enriching our understanding of search across different areas including Human Problem Solving and Design.

RO3- Investigate design process from a search perspective in practice and describe the findings in the form of conceptual frameworks.

Chapters 4 -7 of this research describe the case studies and provide an analysis of the findings, in response to RO3. The study achieved this objective by delineating the search process as it relates to graphic design, automotive design and small domestic appliances and developing three conceptual frameworks illustrating the search process for achieving a holistic design in each of the above sectors. The contributions of these frameworks are twofold: Firstly, they analyse and represent the design process through a search lens, providing both practitioners and academics with detailed insights into the design process. This not only empowers them with a deeper understanding of the necessary processes, resources, and tools for developing products of varying complexity but also highlights characteristics of the design search previously overlooked in major design models, as shown in Table 7-1. Additionally, each case study offers significant value to the research, shedding light on specific domains and thereby enriching our understanding of them.

RO4- Compare the empirical findings with existing literature and identify the gaps.

The achievement of this objective is fulfilled by comparing our research findings with the previously reviewed body of literature. This study reveals a gap in the literature concerning models that fully capture the design process's characteristics as well as the search process for identifying and solving design problems. The empirical insights gained in this study introduce a new perspective on the design process by examining it through a 'design as search' lens. This analysis elucidates how complexity can significantly influence key characteristics of the design process, including iteration, concurrency, and coevolution—elements that previous literature appears to have insufficiently explored.

Furthermore, by analysing the design process from a search perspective, this study highlights the lack of thorough exploration into how various design considerations, such as aesthetics, functionality, and user experience, are intertwined with each other, especially in

complex contexts., to achieve a comprehensive and holistic design approach. This gap signifies a critical area for further scholarly investigation, suggesting that understanding the confluence of aesthetics, functionality, and user experience is essential for a deeper comprehension of the design process, especially when navigating the challenges posed by complex design problems.

8.1.2 RQ2: What Factors Systematically Influence the Nature of Design Search, With particular attention to the Role of Complexity?

RQ2 is particularly impactful to this study as it singles out a particular parameter that influences the activities of designers to identify solutions for holistic design problems. The response to this question enables design practitioners and managers to better design the process and decide on the resources which are required to design holistic products with different degrees of complexity. Also, RQ1 enabled the formulation of the subsequent two research objectives which were contributory to the study in the following ways:

RO5- Identify and investigate elements that influence design search.

Research Question 2 aimed to uncover characteristics that systematically affect the nature of design search. The analysis of empirical findings implied that complexity is a critical factor influencing the design search process. Further analysis in Chapter 7 reaffirmed this finding, identifying complexity as the contingency parameter that influences search activities for holistic design. It also discussed the strategies, processes, and resources that design managers need to employ to manage complexity and respond to its consequences effectively.

The thesis utilizes the NK model's metaphors to better describe holistic designs and the impact of complexity on the search for such designs. It was mentioned that a high level of interaction between elements and attributes of a system is a defining characteristic of holistic designs, resulting in the degree of interaction between the components of a system (K) adopting a high value, close to the system size (N), or the number of components in the system. It was concluded that in holistic design, complexity varies with the system size. The study also revisits the concepts of modular and integral architecture from Ulrich and Ellison (1999), noting that holistic systems represent a specific type of integral architecture where the mapping from functional elements to components is complex (and can be only partially

made explicit, if at all possible) and the interfaces between components are tightly coupled. Thus, in addition to fulfilling Research Objective 5 and identifying complexity as the influencing factor in design search, the thesis further illuminates the concept of holistic complexity and search by linking these definitions to well-established frameworks and concepts from the literature.

RO6- Compare the search processes (from empirical findings) using the identified contingency parameter.

The comparative tables provided in Table 7-3 and Table 7-4 provide an analysis of the features and elements of the search process for low/high complex and low/high holistic designs, and by doing so, build the foundations for developing the framework in Figure 7-4 Search strategies for coping with the complexity and holisticness of the design).

This framework, with its axes spanning from low to high complexity and from less to more holistic design, effectively illustrates how the complexity and holistic nature of a design dictate the adoption of specific search strategies throughout the design process. It categorizes the search strategies into four distinct types: 'Planned and Restricted,' 'Controlled,' 'Creative, Tailor-made,' and 'Creative, Controlled, Harmonized.' In addition to product complexity, each category is shaped by unique project requirements such as brief flexibility, budget considerations, and the scope of innovation expected, all of which influence the search process in identifying and resolving design challenges.

For instance, projects characterized by low complexity and low holistic quality necessitate a focused search within well-defined boundaries due to their tight briefs and limited budgets. These projects often leverage existing designs or ideas with minor adjustments, hence the designation 'Planned and Restricted'. In contrast, designs that are high in complexity but not highly holistic, such as a car update that doesn't necessitate changes in other features and elements of the car, require a very controlled approach. This involves clear strategies for decomposing the problem at the system level to manage complexity and ensure significant iteration to maintain the right interactions (i.e., avoidance of change propagation).

Projects characterised by low complexity, but highly holistic designs demand more flexibility in redefining project briefs and a more adaptable approach to budget and

scheduling. These conditions necessitate a broader search in both problem and solution spaces, encouraging iteration and parallel trials to explore a wide range of possibilities.

Conversely, for projects that are both highly complex and holistic, the search process needs to enable creativity while remaining highly controlled and harmonized. These projects start with open briefs but introduce constraints early on to manage the complexities of the system. This requires a balanced approach to foster creativity while ensuring feasibility through structured problem and solution space exploration.

In answering the proposed research questions, this thesis has satisfied its intended objectives and made a valuable contribution to the understanding of the search in holistic design. More specifically, it has made significant insights into explaining the 'search' process and behaviour of designers in solving 'holistic' design problems.

8.2. Limitations Of the Study

In discussing the limitations of this research, it is crucial to recognise both the inherent methodological challenges and the potential biases or constraints that may affect the study's findings. This research employed a case study approach, specifically utilising polar types sampling within the framework of theoretical sampling from grounded theory. This choice was dictated by the constraints typical of PhD research, such as limited time and resources, and aimed to illuminate the complexities of design processes in the context of holistic design.

8.2.1 Methodological Limitations and Sampling Challenges

The use of polar types sampling was strategic, allowing for the examination of extreme cases to uncover contrasting patterns in design search processes across different levels of complexity and holistic qualities. This method facilitated a focused investigation within the constraints of the study but also introduced limitations regarding the breadth of data and potential for generalisation. While polar sampling is effective for highlighting distinct patterns, its reliance on extreme cases means that more nuanced variations that occur within the middle spectrum might not be as prominently featured. In addition, the selection process for case studies, particularly when using methods like polar types sampling or choosing cases based on their critical, extreme, or revelatory nature, involves a degree of subjectivity. This can introduce biases and limitations in the generalizability of the findings. Although statistical

sampling could offer a more randomized and representative sample, enhancing generalizability, it was deemed impractical for this study. Case study research, especially in complex areas like holistic design, seeks depth over breadth, and statistical sampling's alignment with quantitative research and generalisability does not match the study's qualitative, exploratory focus. Furthermore, the unique dynamics of holistic design, alongside the practical limitations of PhD research, such as resource constraints and the need for in-depth exploration of unique cases, made statistical sampling unsuitable. Therefore, the choice against statistical sampling was driven by the research's aim to develop deep insights and theoretical contributions within the holistic design field, prioritizing theoretical depth and case specificity over broad representativeness.

8.2.2 External Validation and Bias

The absence of external observers during interviews and the potential subjectivity in case selection present notable limitations. These elements may compromise the validity and reliability of the data, impacting the interpretation and generalizability of the findings. Additionally, confirmation bias, where the researcher may prefer data that aligns with pre-existing hypotheses, could have influenced the research outcomes. To counteract these biases and improve data reliability, future research could incorporate strategies such as double coding. Broadening the sampling strategy to encompass a wider array of cases might also provide a more holistic understanding of the design process, thereby addressing existing research gaps.

8.3. Contributions of the Study

Based on the extensive discussions and analyses presented in the thesis, this section highlights the distinct contributions to knowledge made by this study within the field of design. Through a systematic investigation grounded in three streams of literature—design process, complexity theory, and human problem-solving—the research has elucidated the 'search' process and designer behaviour in tackling holistic design challenges of varying complexity. Specifically, this thesis has made the following contributions to knowledge:

1 Challenging the co-evolution narrative in design:

This thesis significantly advances our understanding of design processes through the introduction of a novel framework in Figure 7-4 that articulates how the complexity and holistic nature of a design dictate the adoption of various strategies throughout the design process.

The literature on design coevolution, as reviewed in Section 2.2.4, suggests that problem and solution spaces evolve iteratively throughout the design process, in tandem with the emergence of new information and insights. This enables designers to explore and refine problem statements and solutions concurrently. Such a coevolutionary approach is known to facilitate a dynamic interplay between the identification of problems and the development of solutions.

However, this research challenges the assumption that coevolution persists until project completion in all design scenarios. By investigating high complex and highly holistic design projects, such as those seen in automotive design, it reveals the emergence of a 'freeze' stage, similar to the design-freeze stage in the automotive industry. This stage is characterised by the deliberate limitation of further exploration and refinement in the problem space to solidify design decisions and move towards production. It highlights a practical constraint within the design process where, despite the ideal of ongoing coevolution, the need for project advancement and resource management necessitates a transition to a more fixed design approach.

The introduction of a 'problem freeze' stage into the discourse on design coevolution acknowledges the practical limitations and strategic decisions that shape the trajectory of complex product development. This contribution not only enriches the academic dialogue around the coevolution of design but also provides valuable insights for practitioners in fields where design complexity and holistic integration are paramount. By highlighting the gap between theoretical idealism and industrial pragmatism, this thesis offers a framework that captures the dynamic and often constrained nature of designing for complexity and holisticness.

2 Examination of complexity as a contingency parameter:

The research has pinpointed complexity as a critical factor influencing design search activities, furthering the discourse on how complexity shapes the design process. By linking the impact of complexity on design search to well-established frameworks like the NK model, the study advances our theoretical and practical understanding of complexity in holistic design.

3 Empirical investigation of design search strategies:

Through case studies, this thesis has delineated the search process in the context of graphic design, automotive design, and small domestic appliances. It has identified specific search strategies employed across different levels of complexity and holisticness, categorising these strategies into distinct types and demonstrating how complexity and holistic qualities drive the adoption of particular strategies. This empirical contribution enriches our understanding of how designers navigate the search process in practice.

4 Adaptive mutation: reshaping the search landscape:

One of the key contributions of this thesis lies in the introduction of the concept of "adaptive mutation" in the design of highly complex, holistic products—such as the design of white space cars. This term describes the incorporation of new technologies to alter the design landscape when there is a strong desire to achieve higher performance.

For instance, in Chapter 5 of the thesis, it was discussed that the stylists desire to remove the A-pillar in car design. However, structural barriers and physical limitations prevent this from happening. It was mentioned that design-enabling technologies, such as slim structural beams or display technology, could wrap around the pillar, providing a continuous view and creating the illusion that the A-pillar has been eliminated.

In other words, when faced with a barrier during the design process (such as the A-pillar being unfeasible for stability reasons), the search for solutions aims to artificially alter the landscape. This approach prioritises overcoming barriers without compromising the desired outcome. Rather than merely accepting the existing design constraints, this perspective allows for the manipulation of the design solution landscape to achieve higher performance peaks while avoiding trade-offs.

This perspective challenges the status quo by recognising that the design solution landscape can be intentionally and artificially reshaped—an aspect often overlooked in existing literature on design exploration and search.

5 Development of conceptual frameworks for design process analysis:

This research distinguishes itself through the creation of conceptual frameworks, as presented in Table 2-7 A comparison of reviewed models of design) and Table 2-9 A comparison of theories of design). These frameworks are pivotal in comparing and contrasting the major theories and models of the design process, evaluating their effectiveness in representing the key characteristics of the design process. They not only underline the strengths and limitations of these models and theories but also guide the design community to pursue more inclusive and adaptable methodologies. This detailed comparative analysis contributes significantly to the field of design, illuminating areas that require further theoretical and practical enhancement.

6 Simplifying design language for non-experts:

While it may not be considered a significant contribution to design literature, this research provides substantial benefits to researchers, particularly those without a design background who are keen on delving into the field of design. The researcher's background in Operations Management has endowed the study with distinctive insights. An implicit yet significant contribution of this research is the demystification of design language for non-experts. By developing tools and frameworks that are straightforward and usable by individuals lacking a design background, this thesis improves the understanding and management of the design process. Making the design language more accessible aids cross-disciplinary communication and empowers researchers and project managers from various fields to more effectively engage with design research and practice.

Additionally, by applying methodologies and reasoning more commonly associated with fields like management studies, such as grounded theory and the use of theoretical sampling, to design research, this cross-disciplinary approach may encourage the design research community to consider alternative methodologies. This could potentially offer new

perspectives and investigative tools for design processes, enriching the field with diverse methodological approaches and broadening the scope of design research.

8.4. Future Works

In answering the research questions and fulfilling the specified research objectives, this thesis has made significant contributions to the research topic. However, opportunities for future research have been identified throughout the different stages of this study. This section addresses areas that can leverage the research included in this thesis to offer an extended contribution to the design literature.

8.4.1 Extending het Generality of Research Findings

As suggested in the limitations section, the results generated for this thesis were categorically limited to those design projects with aesthetic dimensions. It would be interesting to extend the study to a larger sample base of complex design projects for products with no substantial aesthetic feature (e.g., information technology or cloud computing infrastructure) to see how the findings of this research would apply to other areas of engineering where decomposition of the problem prove impossible.

In addition, the application of the developed frameworks in practice can be tested to demonstrate the usability of the models in practice and opportunities for making improvements to the models. Such further analysis can also enhance the contribution by providing an opportunity to develop a representative descriptive model that offers a generic visualisation of the search activities in the design process.

8.4.2 Data Collection

The empirical studies that were conducted for this study made a substantial contribution to the understanding of the search in the context of holistic design. However, as mentioned in section 3.5 (Case Study, Challenges and Limitations) the data collection relied on data that could be conveniently collected within the available time for a PhD study. The expansion of the number of cases and the interviews would enable conclusions with greater confidence.

Moreover, although the use of semi-structured interviews gave the flexibility to unfold the questions to get a better understanding of the design process in the intended cases,

however, the data proved to be insufficient in some cases to reveal a full picture of the underlying search activities to complete the design project due to the interviewees' perspective and field of expertise. In particular, as none of the interviewees for the automotive design study was stylists, secondary data from interviews with exterior/interior designers from Motor trades Insight Magazine Online was used. Future research can incorporate data collected from a wider group of experts (including engineers, designers and project managers) enabling the representation of a multilateral view of the design process of large complex products.

8.4.3 Interaction Between Novelty, Complexity and Holisticness

Figure 7-4 describes the search strategies for coping with different degrees of complexity and holisticness of design. One interesting question that can be proposed for future studies is to understand the relevance of the identified search strategies to the project management styles of novel projects. The project management literature recognises unforeseeable uncertainty and complexity as the two critical characteristics of novel projects (e.g., Pitch *et al.,* 2002; De Meyer *et al.* 2006). The different project management styles for managing uncertainty in projects with different degrees of complexity and novelty are also discussed in the literature (Figure 8-1).

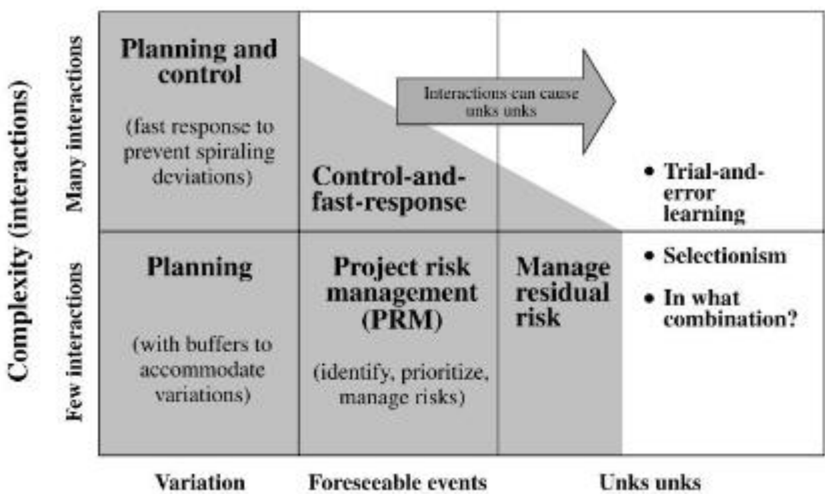

Figure 8-1 A framework of the source of uncertainty in project management (Loch et al., 2006)

Two fundamental approaches of selectionism and learning have been defined in prior literature as approaches to manage innovation in the presence of unforeseeable uncertainty

and complexity. "Selectionism refers to trying many solutions in parallel and selecting the best ex post. Trial and error learning refers to flexibly adjusting project activities and targets to new information, as it becomes available (unplanned)" (Sommer and Loch, 2004). As discussed in this thesis, these two approaches are the fundamental building blocks of the human search process. Therefore, the relevance of the project management style of the novel projects and search strategies for holistic design is an area which would benefit from further research.

In addition, as can be seen from Figure 7-2 those designs that were considered as holistic, were products that encompassed some degree of project novelty, as they were tailor-made to customer requirements and required extensive search in the problem as well as solution space. Therefore, one area that can be explored further is the relevance between project novelty and holistic design. The project management literature recognises the correlation between novelty and uncertainty in the project (e.g., Brockhoff, 2006; De Meyer et al., 2006). It would be interesting to see if there is any relationship between the holistic architecture of the design, the presence of a high degree of uncertainty and the novelty of the project. In this thesis, it was argued that one characteristic of holistic architecture is related to the complexity of performance function, and the fact that it may not be possible to fully map customer preference as a function of product attributes. In other words, by defining the attributes right, one cannot guarantee the product's success. Hence, the landscape in such cases needs to be intuitively, extensively (through parallel search) and iteratively searched for a whole that pleases the customer. For example, one of the observations made in this thesis was that one way of finding the gap in the market for car companies is congregating attributes that pleased the customers in different previous models into one new product. That is, they ask questions like this: people liked the size of this car, but the ride quality of the other car, can we create something that brings the two together? For the new combination (the new whole) to work, extensive search, trade-offs and adjustments are needed.

While previous literature has identified complexity as a key characteristic of novel projects, it might be the case that this characteristic is holisticness, and not any form of complexity, keeping in mind that as discussed in section 7.1 holistic architecture are a specific form of complex (integral) architectures.

To conclude, several preliminary hypotheses can be proposed to be tested further:

- In novel projects, holisticness leads to uncertainty and not any type of complexity.
- In holistic systems, the need for novelty (e.g., defining new attributes, trying new interfaces, introductions of new technologies) is an approach to managing uncertainty.

8.5. Conclusion

The purpose of this study was to characterise and explain the 'search' process in solving 'holistic' design problems with different degrees of complexity. The formulation of the hypotheses was helpful in the formulation and placement of research objectives congruent to the research phenomenon. The success of the study is evident in the fulfilment of the research objectives, the extensive findings that match the research questions and the reliability and congruency of the research findings to past-conducted studies. Besides, this study successfully identifies a research gap in the holistic design search process and fills the gaps with the findings made within its scope. In addition, the application of the research findings makes a significant contribution to the existing body of research, albeit within the limit of design of those groups of products with aesthetic dimensions. And finally, the study proposes opportunities for future research that can leverage the findings and analysis of this research.

REFERENCES

Abbott, L. (1955), Quality and Competition: An Essay in Economic Theory, New York: Columbia University Press.

AitSahlia, F., Johnson, E. and Will, P. (1995), 'Is concurrent engineering always a sensible proposition?', IEEE Transactions on Engineering Management, 42(2), pp. 166-170.

Alexander, C. (1964), Notes on the Synthesis of Form, Cambridge, Mass.: Harvard University Press.

Alexiou, K. and Zamenopoulos, T. (2008) 'Design as a social process: A complex systems perspective', Futures, 40(6), pp. 586-595.

Altenberg, L. (1997) 'NK fitness landscapes', Handbook of evolutionary computation, pp. 7-2.

Altshuller, G. L. S., (Trans.) (1994) And suddenly the inventor appeared: TRIZ, the theory of inventive problem solving, Worcester, Mass.: Technical Innovation Center.

America, M.-B. L. (2013) The design process at Mercedes-Benz. Available at: http://www.la.mercedes-benz.com/content/latina/mpc/mpc_latina_website/en/home_mpc/passengercars/home/passengercars_world/design/design_process.html (Accessed: 9/12/2013).

Anderson, J. R. (2015) Cognitive psychology and its implications. Eighth edition. edn. NY, US: Worth Publishers.

Andrews, D. (1981) 'Creative Ship Design', Transactions of RINA,207, pp .8-9.

Archer, L. B. (1965) Systematic method for designers. London: Council of Industrial Design.

Arnheim, R. (1993) 'Sketching and the Psychology of Design', Design Issues, 9(2), pp. 15-19.

Arora, J. S. (2004) Introduction to optimum design. 2nd ed., London: Elsevier/Academic Press.

Asimow, M. (1962) Introduction to design. New York: Prenitce-Hall.

Auerswald, P., Kauffman, S., Lobo, J. and Shell, K. (2000) 'The production recipes approach to modelling technological innovation: An application to learning by doing', Journal of Economic Dynamics and Control, 24(3), pp. 389-450.

Banathy, B. H. (1990) 'Design: A journey to create the future map of the journey, in Collen, A. (ed.) Evolutionary Guidance Systems. San Francisco: Saybrook Institute, pp. 197–204.

Banathy, B. H. (1996) Designing social systems in a changing world. New York; London: Plenum

Press.

Barros, G. (2010) 'Herbert A. Simon and the concept of rationality: Boundaries and procedures', Brazilian Journal of Political Economy, 30(3 (119)), pp. 455-472.

Basalla, G. (1988) 'The Evolution of Technology', Cambridge, UK: Cambridge University Press. 1988)

Bassler, D., Oehmen, J., Seering, W., Ben-Daya M., (2011) 'A comparison of the integration of Risk management Principles in Product Development Approaches', Proceedings of the 18th International Conference on Engineering Design (ICED 11), Copenhagen, Denmark, 15 - 18 August, pp.306-316.

Bates, M. J. (1979) 'Information search tactics', Journal of the American Society for Information Science, 30(4), pp. 205-214.

Benbasat, I., Goldstein, D. K., & Mead, M. (1987). The Case Research Strategy in Studies of Information Systems. MIS Quarterly, 11, pp: 369-386. http://dx.doi.org/10.2307/248684

Bhise, V. D. (2012) Ergonomics in the automotive design process. Boca Raton, Fla.: CRC; London: Taylor & Francis [distributor].

Birtley, N. (2002) 'Body design: The styling process', in Happian-Smith, J. (ed.) An Introduction to Modern Vehicle Design Oxford, UK: Butterworth-Heinemann.

Blackburn, J. D., Hoedemaker, G. and Wassenhove, L. N. v. (1996) 'Concurrent software engineering: prospects and pitfalls', IEEE Transactions on Engineering Management, 43(2), pp. 179-188.

Blessing, L. T. M., Chakrabarti, A. and Blessing, L. T. M. D. r. m. (2009) DRM, a design research methodology. Dordrecht; London: Springer.

Blessing, L. T. M., Chakrabarti, A. and Wallace, K. M. (1992) ' Some issues in engineering design research', in N., C. (ed.) OU/SERC Design Methods Workshop. Milton Keynes, UK.: Open University.

Bloch, P. H. (1995) 'Seeking the Ideal Form: Product Design and Consumer Response', Journal of Marketing, 59(3), pp. 16-29.

Boehm, B. 'Spiral Development: Experience, Principles, and Refinements', USC-SEI Workshop on Spiral Development, Experience and Implementation Challenges, USC, February 9-11.

Boehm, B. and Bose, P. 'A collaborative spiral software process model based on Theory W'. Proceedings of the Third International Conference on the Software Process. Applying the Software Process, 10-11 Oct 1994, 59-68.

Boehm, B. W. (1988) 'A spiral model of software development and enhancement', Computer, 21(5), pp. 61-72.

Boehm, B. W. (1991) 'Software risk management: principles and practices', IEEE Software, 8(1), pp. 32-41.

Bolc, L. and Cytowski, J. (1992) Search methods for artificial intelligence. London: Academic Press.

Boud, D., Keogh, R. and Walker, D. (1985) 'Promoting reflection in learning: a model (1)', in Dawsonera, Boud, D., Keogh, R. and Walker, D. (eds.) Reflection: turning experience into learning. London: Kogan Page, pp. 18-40.

Braha, D. and Maimon, O. (1997) 'The Design Process: Properties, Paradigms, and Structure', Ieee Transactions on Systems, Man, And Cybernetics—Part A: Systems and Humans, 27(2), pp. 146-166.

Braha, D. and Reich, Y. (2003) 'Topological structures for modelling engineering design processes', Research in Engineering Design, 14(4), pp. 185-199.

Brockhoff, K. (2006) 'On the Novelty Dimension in Project Management', Project Management Journal, 37(3), pp. 26-36.

Brooks, F. P. (2010) The design of design: essays from a computer scientist. Boston, Mass.; London: Addison-Wesley.

Browning, T. R. (2001) 'Applying the design structure matrix to system decomposition and integration problems: a review and new directions', IEEE Transactions on Engineering Management, 48(3), pp. 292-306.

Browning, T. R. and Eppinger, S. D. (2002) 'Modelling impacts of process architecture on cost and schedule risk in product development', IEEE Transactions on Engineering Management, 49(4), pp. 428-442.

Browning, T. R., Fricke, E. and Negele, H. (2006) 'Key concepts in modelling product development processes', Systems Engineering, 9(2), pp. 104-128.

Browning, T. R. and Ramasesh, R. V. (2007) 'A Survey of Activity Network-Based Process Models for Managing Product Development Projects', Production and Operations Management, 16(2), pp. 217-240.

Bruce, M. and Bessant, J. (2002) Design in business: strategic innovation through design. Harlow: Financial Times Prentice Hall.

Buchanan, R. (1992) 'Wicked Problems in Design Thinking', Design Issues, 8(2), pp. 5-21.

Buchanan, R. (2001) 'Design Research and the New Learning', Design Issues, 17(4), pp. 3-23.

Buede, D. M. (2000) The engineering design of systems: models and methods. New York; Chichester: Wiley.

Buxton, I. L. (1972) 'Engineering Economics Applied to Ship Design', Transactions of RINA, 114.

Campbell, M., Egan, M., Lorenc, T., Bond, L., Popham, F., Fenton, C. and Benzeval, M. (2014) 'Considering methodological options for reviews of theory: illustrated by a review of theories linking income and health', Systematic Reviews, 3(1), pp. 114.

Charmaz, K. (2006) Constructing grounded theory. London; Thousand Oaks, Calif.: Sage Publications.

Chew, W. B., Leonard-Barton, D. and Bohn, R. E. (1991) 'Beating Murphy's Law', Mit Sloan Management Review

Chijindu, E. V. C. (2012) 'Search in Artificial Intelligence Problem Solving ', African Journal of Computing & ICT, 5(5).

Choulier, D., Coatanéa, E. and Forest, J. 'The Engineering Design CK Theory: Contributions and Limits'. 22nd International Conference on Design Theory and Methodology, Montréal, Canada., pp.83-92.

Chris De, B. (1987) 'The Evolutionary Paradigm and the Economics of Technological Change', Journal of Economic Issues, 21(2), pp. 751-762.

Chun Tie, Y., Birks, M., & Francis, K. (2019). Grounded theory research: A design framework for novice researchers. SAGE open medicine, 7, doi: https://doi.org/10.1177/2050312118822927

Churchman, C. W. (1979) The systems approach and its enemies. New York: Basic Books.

Churchman, C. W. (1987) 'The philosophy of design', International Congress on Planning and Design Theory, Boston Park Plaza, August 17-20, Boston, MA, pp. 17-20.

CK-Theory.org (2017) C-K Theory. Available at: https://www.ck-theory.org/?lang=en (Accessed: 29/11/2017).

Clark, K. B., and T. Fujimoto (1991) Product Development Performance: Strategy, Organization, and Management in the World Auto Industry. Boston: Harvard Business School Press

Clarke, J., Dolado, J. J., Harman, M., Hierons, R., Jones, B., Lumkin, M., Mitchell, B., Mancoridis, S., Rees, K., Roper, M. and Shepperd, M. (2003) 'Reformulating software engineering as a search problem', IEE Proceedings - Software, 150(3), pp. 161-175.

Clarkson, P. J. and Hamilton, J. R. (2000) ''Signposting', A Parameter-driven Task-based Model of the Design Process', Research in Engineering Design, 12(1), pp. 18-38.

Cohen, L., Manion, L. A. and Morrison, K. A. (2007) Research Methods in Education. 6th edn. Taylor & Francis e-Library: Routledge.

Cooper, L. P. (2003) 'A research agenda to reduce risk in new product development through knowledge management: a practitioner perspective', Journal of Engineering and Technology Management, 20(1), pp. 117-140.

Cooper, R. G. (1990) 'Stage-gate systems: A new tool for managing new products', Business Horizons, 33(3), pp. 44-54.

Cordero, R. (1991) 'Managing for speed to avoid product obsolescence: A survey of techniques', Journal of Product Innovation Management, 8(4), pp. 283-294.

Cox G. and Zoe D. (2005) Cox Review of Creativity in Business: Building on the Uk's Strengths. Norwich: TSO.

Creswell, J.W. (2014) Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. Sage Publications.

Creusen, M. E. H. and Schoormans, J. P. L. (2005) 'The Different Roles of Product Appearance in Consumer Choice', Journal of Product Innovation Management, 22(1), pp. 63-81.

Crilly, N., Moultrie, J. and Clarkson, P. J. (2004) 'Seeing things: consumer response to the visual domain in product design', Design Studies, 25(6), pp. 547-577.

Crilly, N., Moultrie, J., & Clarkson, P. J. (2009). Shaping things: Intended consumer response and the other determinants of product form. Design Studies, 30(3), pp.224–254.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. Design Studies, 38, pp. 54-91.

Crilly, N., & Cardoso, C. (2017). Where next for research on fixation, inspiration and creativity in design? Design Studies, 50, pp. 1–38. https://doi.org/10.1016/j.destud.2017.02.001

Crilly, N., (2021) 'The Evolution of “Co-evolution” (Part II): The Biological Analogy, Different Kinds of Co-evolution, and Proposals for Conceptual Expansion, She Ji: The Journal of Design, Economics, and Innovation, Volume 7, Issue 3, Pages 333-355.

Cross, N. (1977) The automated architect. London: Pion.

Cross, N. (1994) Engineering design methods: strategies for product design. 2nd ed. edn. Chichester: Wiley.

Cross, N. (2000) Engineering design methods: strategies for product design. 3rd ed. edn. Chichester: Wiley.

Daly, S., McGowan, A. and Papalambros, P. (2013) 'Using qualitative research methods in

engineering design research'. 19th International Conference on Engineering Design (ICED13), 19-22 August, Seoul, Korea, pp. 203-212.

Daniel, J., Medland, T. and Newnes, L. (2007) 'Graphical representation of key iterations during the design process'. Proceedings of ICED 2007, the 16th International Conference on Engineering Design, 28 - 31 August, Paris, France, 727-728.

Darke, J. (1979) 'The primary generator and the design process', Design Studies, 1(1), pp. 36-44.

Dasgupta, S. (1992) 'Herbert Simon's `Science of Design': two decades later'. First International Conference on Intelligent Systems Engineering, 19-21 Aug 1992, Edinburgh, UK, pp.171-178.

De Bresson, C. (1987) 'The Evolutionary Paradigm and the Economics of Technological Change', Journal of Economic Issues, 21(2), pp. 751-762.

De Meyer, A., Loch, C. H. and Pich, M. T. (2006) Management of novel projects under conditions of high uncertainty. Cambridge Judge Business School.

Design Council, (2005) 'The Design Process: What is the Double Diamond?' Available at: https://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond (Accessed: 16/02/2018).

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

Drost, E. (2011) 'Validity and Reliability in Social Science Research', Education Research and Perspectives, 38, pp. 105-124.

Dym, C. L., Little, P., Orwin, E. J. and Spjut, R. E. (2009) Engineering design: a project-based introduction. 3rd ed. / with Elizabeth J. Orwin and R. Erik Spjut. edn. Hoboken, N.J.: Wiley.

Eckert, C. and Stacey, M. (2000) 'Sources of inspiration: a language of design', Design Studies, 21(5), pp. 523-538.

Eckert, C. M., Wynn, D. C., Maier, J. F., Albers, A., Bursac, N., Xin Chen, H. L., Clarkson, P. J., Gericke, K., Gladysz, B. and Shapiro, D. (2017) 'On the integration of product and process models in engineering design', Design Science, 3.

Eisenbart, B., Gericke, K. and L., B. 'A Framework for Comparing Design Modelling Approaches across Disciplines'. Proceedings of the 18th International Conference on Engineering Design (ICED 11), Copenhagen, Denmark., 15 - 18 AUGUST.

Eisenhardt, K. M. (1989) 'Building Theories from Case Study Research', The Academy of Management Review, 14(4), pp. 532-550.

Eisenhardt, K. M. and Graebner, M. E. (2007) 'Theory building from cases: Opportunities and challenges', Academy of Management Journal, 50(1), pp. 25-32.

Eisenhardt, K. M. and Tabrizi, B. N. (1995) 'Accelerating Adaptive Processes: Product Innovation in the Global Computer Industry', Administrative Science Quarterly, 40(1), pp. 84-110.

Ekebergh, M. (2007) 'Lifeworld-based reflection and learning: a contribution to the reflective practice in nursing and nursing education', Reflective Practice, 8(3), pp. 331-343.

Elster, J. (1983) Sour grapes: studies in the subversion of rationality. Cambridge: Cambridge University Press.

Eppinger, S. D. and Browning, T. R. (2012) Design structure matrix methods and applications. Cambridge, Mass.: MIT Press.

Eppinger, S. D., Nukala, M. V. and Whitney, D. E. (1997) 'Generalised models of design interation using signal flow graphs', Research in Engineering Design, 9(2), pp. 112-123.

Ertas, A. and Jones, J. C. (1996) The engineering design process. 2nd ed. edn. Chichester: Wiley.

Ethiraj, S. K. and Levinthal, D. (2004) 'Bounded Rationality and the Search for Organizational Architecture: An Evolutionary Perspective on the Design of Organizations and Their Evolvability', Administrative Science Quarterly, 49(3), pp. 404-437.

Evans, J. H. (1959) 'Basic Design Concepts', Journal of the American Society for Naval Engineers, 71(4), pp. 671-678.

Evbuomwan, N. F. O., Sivaloganathan, S. and Jebb, A. (1996) 'A Survey of Design Philosophies, Models, Methods and Systems', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 210(4), pp. 301-320.

Fandino, W. (2019) 'Formulating a good research question: Pearls and pitfalls', Indian journal of anaesthesia, 63(8), pp. 611-616.

Finger, S. and Dixon, J. R. (1989) 'A review of research in mechanical engineering design. Part I: Descriptive, prescriptive, and computer-based models of design processes', Research in Engineering Design, 1(1), pp. 51-67.

Finke, R. A., Ward, T. B. and Smith, S. M. (1992) Creative cognition: theory, research, and applications. Cambridge, Mass.; London: MIT Press.

Fischer, F. (1990) Technocracy and the politics of expertise. Newbury Park, Calif.; London: Sage Publications.

Fish, J. and Scrivener, S. (1990) 'Amplifying the Mind's Eye: Sketching and Visual Cognition',

Leonardo, 23(1), pp. 117-126.

Fleming, L. and Sorenson, O. (2004) 'Science as a map in technological search', Strategic Management Journal, 25(8-9), pp. 909-928.

Fiol, C.M. and Huff, A.S., (1992), Maps for Managers: Where Are We? Where Do We Go From Here?, Journal of Management Studies, 29, pp:267-285. https://doi.org/10.1111/j.1467-6486.1992.tb00665.x

Fontana, A. and Frey, J. H. (2005) 'The Interview: From Neutral Stance to Political Involvement. ', in Denzin, N.K. and Lincoln, Y.S. (eds.) The Sage handbook of qualitative research. Thousand Oaks, CA: Sage Publications., pp. 695-727.

Forsberg, K. and Mooz, H. (1998) 'System Engineering for Faster, Cheaper, Better', INCOSE International Symposium, 8(1), pp. 917-927.

French, M. J. (1999) Conceptual design for engineers. 3rd ed. edn. London: Springer.

Frenken, K. (2006a) 'A fitness landscape approach to technological complexity, modularity, and vertical disintegration', Structural Change and Economic Dynamics, 17(3), pp. 288-305.

Frenken, K. (2006b) 'Technological innovation and complexity theory', Economics of Innovation and New Technology, 15(2), pp. 137-155.

Frenken, K., Marengo, L. and Valente, M. (1999) 'Interdependencies, Nearly-Decomposability and Adaptation', in Brenner, T. (ed.) Computational Techniques for Modelling Learning in Economics. Boston, MA: Springer US, pp. 145-165.

Frenken, K. and Valente, M. (2004) A fitness landscape approach to decentralised problem-solving. In: University, U. (ed.).

Fricke, E., Negele, H., Schrepfer, L., Dick, A., Gebhard, B. and Hartlein, N. (1998) 'Modelling of concurrent engineering processes for integrated systems development'. 17th DASC. AIAA/IEEE/SAE. Digital Avionics Systems Conference. Proceedings (Cat. No.98CH36267), 31 Oct.-7 Nov. 1998, B13/1-B13/8 vol.1.

Funke, J. (2010) 'Complex problem solving: a case for complex cognition?', Cognitive Processing, 11(2), pp. 133-142.

Gary, S. L., Joseph, G. M. and Albert, S. P. (1996) 'Marketing and Discontinuous Innovation: The Probe and Learn Process', California Management Review, 38(3), pp. 8-37.

Gavetti, G. and Levinthal, D. (2000) 'Looking Forward and Looking Backward: Cognitive and Experiential Search', Administrative Science Quarterly, 45(1), pp. 113-137.

Gavriluk, V. (2023). ‘What is Holistic Design? Pictures & Examples’, Arounda., Available at:, https://arounda.agency/blog/what-is-holistic-design-pictures-and-examples, Accessed

02/02/2024.

Gericke, K. and L., B. (2011) 'Comparisons of Design Methodologies and Process Models across Disciplines: A Literature Review', Proceedings of the 18th International Conference on Engineering Design (ICED 11), Copenhagen, Denmark., 15 - 18 August.

Gerrits, L. and Marks, P. (2014a) 'The evolution of Wright's (1932) adaptive field to contemporary interpretations and uses of fitness landscapes in the social sciences', Biology & Philosophy, pp. 1-21.

Gerrits, L. and Marks, P. (2014b) 'The interpretations and uses of fitness landscapes in the social sciences', working paper, available at: https://repub.eur.nl/pub/51659/Working-paper-LG-PM.pdf

Gibbs, G. (2007) Analyzing Qualitative Data London, England. Available at: http://methods.sagepub.com/book/analyzing-qualitative-data (Accessed: 11/12/2017).

Gigerenzer, G. and Selten, R. (2001) Bounded rationality: the adaptive toolbox. Cambridge, Mass.; London: MIT Press.

Glaser, B. G. and Strauss A. (1967) The discovery of grounded theory: strategies for qualitative research. New York: Aldine de Gruyter.

Goel, S. (2010) 'Design is a Reflective Practice: A Summary of Schön's Views', Engineering & Computing Education: Reflections and Ideation. Available at: https://goelsan.wordpress.com/2010/08/20/design-is-a-reflective-practice-a-summary-of-schons-views/ 2019].

Goel, V. and Pirolli, P. (1992) 'The structure of Design Problem Spaces', Cognitive Science, 16(3), pp. 395-429.

Goldenberg, J. and Mazursky, D. (2002) Creativity in product innovation. Cambridge: Cambridge University Press.

Goldfarb, R. S. and Ratner, J. (2008) '"Theory" and "Models": Terminology Through the Looking Glass', Econ Journal Watch, 5(1), pp. 91-108.

Goldkuhl, G. (2004) 'Design Theories in Information Systems - A Need for Multi-Grounding', Journal of Information Technology Theory and Application (JITTA), 6(2), pp. 59-72.

Goldschmidt, G. (1991) 'The dialectics of sketching', Creativity Research Journal, 4(2), pp. 123-143.

Goodchild, M. F. (1992) 'Geographical data modelling', Computers & Geosciences, 18(4), pp. 401-408.

Gorelick, R. (2011) 'What is theory?', Ideas in Ecology and Evolution, 4, pp. 1-10.

Green, J., Willis, K., Hughes, E., Small, R., Welch, N., Gibbs, L. and Daly, J. (2007) 'Generating best evidence from qualitative research: the role of data analysis', Australian and New Zealand Journal of Public Health, 31(6), pp. 545-550.

Greenwood, J. (1993) 'Reflective practice: a critique of the work of Argyris and Schön', Journal of Advanced Nursing, 18(8), pp. 1183-1187.

Greenwood, R. and Suddaby, R. (2006) 'Institutional Entrepreneurship in Mature Fields: The Big Five Accounting Firms', The Academy of Management Journal, 49 (1), pp. 27-48.

Gregory, R. W. (2011) 'Design Science Research and the Grounded Theory Method: Characteristics, Differences, and Complementary Uses', in Heinzl, A., Buxmann, P., Wendt, O. and Weitzel, T. (eds.) Theory-Guided Modelling and Empiricism in Information Systems Research. Heidelberg: Physica-Verlag HD, pp. 111-127.

Gregory, S. A. E. (1966) The design method. Springer Science+Business Media, LLC, New York.

Guest G., Bunce A. and Johnson L. (2006), 'How many interviews are enough? An experiment with data saturation and variability', Journal of Field Methods, 18(1), pp.59–82. doi: 10.1177/1525822X05279903.

Huang H-Z, Gu Y-K (2006) 'Development Mode Based on Integration of Product Models and Process Models', Concurrent Engineering: Research and Applications, 14(1).

H.W.J. Rittel (1984) ' Second-Generation Design Methods, Developments in Design Methodology,' in (Ed.), N.C. (ed.): John Wiley and Sons, New York, pp. 317-327.

Halford, G. S., Maybery, M. T., O'Hare, A. W. and Grant, P. (1994) 'The Development of Memory and Processing Capacity', Child Development, 65(5), pp. 1338-1356.

Hatchuel, A., (2001) 'Towards Design Theory and Expandable Rationality: The Unfinished Program of Herbert Simon', Journal of Management & Governance, 5, pp. 260–273, doi: https://doi.org/10.1023/A:1014044305704

Hatchuel, A. and Weil, B. (2002) 'C-K theory: Notions and applications of a unified design theory'. Herbert Simon International Conference on Design Sciences, Lyon, 15-16 March.

Hatchuel, A. and Weil, B. (2003) 'A new approach of innovative design: an introduction to CK theory'. International Conference on Engineering Design (ICED'03), Stockholm, Sweden, August 19-21, pp.109–124.

Hatchuel, A. and Weil, B. (2003b) A new approach of innovative design: an introduction to CK theory.

Hatchuel, A. and Weil, B. (2009) 'C-K design theory: an advanced formulation', Research in Engineering Design, 19(4), pp. 181-192.

Hausman, D. M. (1992) ‘The inexact and separate science of economics’, Cambridge: Cambridge University Press, doi:10.1017/CBO9780511752032.

Hazelrigg, G. A. (1998) 'A Framework for Decision-Based Engineering Design', Journal of Mechanical Design, 120(4), pp. 653-658.

Hazelrigg, G. A. (1999) 'On the Role and Use of Mathematical Models in Engineering Design', Journal of Mechanical Design, 121(3), pp. 336-341.

Heskett, J. (2005) Design: a very short introduction, Oxford: Oxford University Press.

Higuera-Trujillo, J. L., Llinares, C. and Macagno, E. (2021), ‘The cognitive-emotional design and study of architectural space: a scoping review of neuroarchitecture and its precursor approaches’, Sensors, 21(6), 2193, pp. 1-49, doi: https://doi.org/10.3390/s21062193

Hills, T. T. and Dukas, R. (2012) 'The Evolution of Cognitive Search ', in Todd, P.M., Hills, T.T. and Robbins, T.W. (eds.) Cognitive Search: Evolution, Algorithms, and the Brain (Strüngmann Forum Report). Cambridge, MA: MIT Press.

Hills, T. T. and Hertwig, R. (2010) 'Information search in decisions from experience. Do our patterns of sampling foreshadow our decisions?', Psychological Science, 21, pp. 1787–1792.

Hobday, M. (2000) 'The project-based organisation: an ideal form for managing complex products and systems?', Research Policy, 29(7), pp. 871-893.

Holland, J. H. (1986) Induction: processes of inference, learning and discovery. Cambridge, Mass.; London: MIT Press.

Holmström, J., Ketokivi, M. and Hameri, A.-P. (2009) 'Bridging Practice and Theory: A Design Science Approach', Decision Sciences, 40(1), pp. 65-87.

Holyoak, K. J. and Thagard, P. (1995) Mental leaps: analogy in creative thought. Cambridge, Mass. ; London: MIT Press.

Hubka, V. and Eder, W. E. (1996) Design science: introduction to the needs, scope and organization of engineering design knowledge. London: Springer.

Huppatz, D. (2015) 'Revisiting Herbert Simon's Science of Design', Design Issues, 31(2), pp. 29-40.

Hutchinson, J. M. C., Stephens, D. W., Bateson, M., Couzin, I., Dukas, R., Giraldeau, L.-A., Hills, T. T., Méry, F. and Winterhalder, B. (2012) 'Searching for Fundamentals and Commonalities of Search', in Todd, P.M., Hills, T.T. and Robbins, T.W. (eds.) Cognitive Search: Evolution, Algorithms, and the Brain (Strüngmann Forum Report). Cambridge, MA: MIT Press.

Iacono, J. C., Brown, A. and Holtham, C. (2011) 'The use of the case study method in theory

testing: The example of steel emarketplaces', The Electronic Journal of Business Research Method, 9(1), pp. 57-65.

Ian, P. M. (2004) 'Manufacturing strategy: understanding the fitness landscape', International Journal of Operations & Production Management, 24(2), pp. 124-150.

Insight, M. (2013). Interview: Icona Vulcano designer Samuel Chuffart believes 'good design can change the world, Available at: https://motortradesinsight.co.uk/article_page.asp?id=726&topic=interview-icona-vulcano-designer-samuel-chuffart-believes-good-design-can-change-the-world (Accessed: 1/10/2017).

Interaction Design Foundation - IxDF. ‘What is Holistic Design?’ Interaction Design Foundation - IxDF. Available at: https://www.interaction-design.org/literature/topics/holistic-design (accessed 04/02/2024).

Isenberg, J. D. (1984) 'How Senior Managers Think', Harvard Business Review, 62 (November-December), pp. 81-90.

Jackson, M. C. (2003) Systems thinking: creative holism for managers. Chichester, West Sussex.: John Wiley & Sons.

James, W. (1890) The Principles of Psychology. New York. [S.l.]: Macmillan and Co. Ltd.

Janneke, B., Marielle, E. H. C. and Jan, P. L. S. (2009) 'How Consumers Perceive Product Appearance: The Identification of Three Product Appearance Attributes', International Journal of Design; 3(3), pp. 27-35.

Johansson-Sköldberg, U., Woodilla, J. and Çetinkaya, M. (2013) 'Design Thinking: Past, Present and Possible Futures', Creativity and Innovation Management, 22(2), pp. 121-146.

Jonassen, D. H. (2010) 'Learning to solve problems: A handbook for designing problem-solving learning environments', Learning to Solve Problems: A Handbook for Designing Problem-Solving Learning Environments, pp. 1-437.

Jones, J. C. (1970) Design methods: seeds of human futures. London: Wiley-Interscience.

Jun, H. and Suh, H. (2008) 'A Modelling Framework for Product Development Process Considering its Characteristics', IEEE Transactions on Engineering Management, 55(1), pp. 103-119.

Khalid, H.M. and Helander, M.G. (2006) ‘Customer Emotional Needs in Product Design’, Concurrent Engineering, 14(3), pp.197-206, doi:10.1177/1063293X06068387

Khandani, S. (2005) Engineering Design Process: Education Transfer Plan, https://dphu.org/uploads/attachements/books/books_2547_0.pdf

Kannengiesser, U. and Gero, J. (2017) 'Can Pahl and Beitz' systematic approach be a predictive model of designing?', 3.

Kauffman, S. and Levin, S. (1987) 'Towards a general theory of adaptive walks on rugged landscapes', Journal of Theoretical Biology, 128(1), pp. 11-45.

Kauffman, S. and Macready, W. (1995) 'Technological evolution and adaptive organizations: Ideas from biology may find applications in economics', Complexity, 1(2), pp. 26-43.

Kauffman, S. A. (1993) The origins of order: self-organization and selection in evolution. New York, N.Y.: OUP.

Kauffman, S. A. and Johnsen, S. (1991) 'Coevolution to the edge of chaos: Coupled fitness landscapes, poised states, and coevolutionary avalanches', Journal of Theoretical Biology, 149(4), pp. 467-505.

Kauffman, S. A. and Weinberger, E. D. (1989) 'The NK model of rugged fitness landscapes and its application to maturation of the immune response', Journal of Theoretical Biology, 141(2), pp. 211-245.

Kazakci, A. and Tsoukiàs, A. 'Extending the C–K design theory: A theoretical background for personal design assistants'. DESIGN 2004, the 8th International Design Conference, Dubrovnik, Croatia.

Keizer, J. A., Halman, J.I.M., Song, M. (2002) 'From experience - applying the risk diagnosing methodology', Journal of Product Innovation Management 19(3), pp. 213-232. .

Kesselring, F. (1964) 'Technisch-wirtschaftliches Konstruieren (Technical-Economic Designing),' VDI-Zeitschr, 106(30).

Khurana, A. and Rosenthal, S. R. (1998) 'Towards holistic "front ends" in new product development', Journal of Product Innovation Management, 15(1), pp. 57-74.

Kim, H. M., Jiang, T., Michelena, N. F. and Papalambros, P. Y. (2003) 'Target Cascading in Optimal System Design', Journal of Mechanical Design, 125(3), pp. 474-480.

Kimura, F. (1997) 'Issues in Styling and Engineering Design', CIRP Annals - Manufacturing Technology, 46(2), pp. 527-534.

Kokkolaras, M., Fellini, R., Kim, H. M., Michelena, N. F. and Papalambros, P. Y. (2002) 'Extension of the target cascading formulation to the design of product families', Structural and Multidisciplinary Optimization, 24(4), pp. 293-301.

Kopec, D. and A., M. T. (2001) Artificial Intelligence: Search Methods. Available at: http://spider.sci.brooklyn.cuny.edu/~kopec/Publications/Publications/O_5_AI.pdf, (Accessed: 25/04/2017)

Koro-Ljungberg, M. and Douglas, E. P. (2008) 'State of Qualitative Research in Engineering Education: Meta-Analysis of JEE Articles, 2005–2006', Journal of Engineering Education, 97(2), pp. 163-175.

Krishnamurty, S. (2006) 'Normative Decision Analysis in Engineering Design', in Lewis, K.E., Chen, W. and Schmidt, L.C. (eds.) Decision Making in Engineering Design. New York, NY: ASME.

Krishnan, V., Eppinger, S. D. and Whitney, D. E. (1997) 'A Model-Based Framework to Overlap Product Development Activities', Management Science, 43(4), pp. 437-451.

Lawson, B. (2005) How designers think: the design process demystified. 4th ed. edn. Oxford: Elsevier.

Lawson, B. and Dorst, K. (2009) Design expertise. Oxford: Architectural Press.

Lawson, M. and Karandikar, H. M. (1994) 'A Survey of Concurrent Engineering', Concurrent Engineering, 2(1), pp. 1-6.

Laxman, K. (2010) 'A conceptual framework mapping the application of information search strategies to well and ill-structured problem solving', Computers & Education, 55(2), pp. 513-526.

Lemon, K. N., and Verhoef, P. C. (2016). 'Understanding Customer Experience Throughout the Customer Journey', Journal of Marketing, 80(6), pp. 69–96, doi: https://doi.org/10.1509/jm.15.0420

Lenox, M. J., Rockart, S. F. and Lewin, A. Y. (2006) 'Interdependency, Competition, and the Distribution of Firm and Industry Profits', Management Science, 52(5), pp. 757-772.

Lenox, M. J., Rockart, S. F. and Lewin, A. Y. (2007) 'Interdependency, Competition, and Industry Dynamics', Management Science, 53(4), pp. 599-615.

Levinthal, D. A. (1997) 'Adaptation on Rugged Landscapes', Management Science, 43(7), pp. 934-950.

Lewis, K. E., Chen, W. and Schmidt, L. C. (2006) Decision Making in Engineering Design. New York: ASME PRESS.

Lewis, S. (2015) Design Process: Tips from an Expert Graphic Designer. Designer HubSpot. Available at: http://designers.hubspot.com/blog/graphic-designer-design-process-tips (Accessed: 25/08/2016 2016).

Liikkanen, L. A. and Perttula, M. (2009) 'Exploring problem decomposition in conceptual design among novice designers', Design Studies, 30(1), pp. 38-59.

Loch, C. (2000) 'Tailoring product development to strategy: case of a European technology

manufacturer', European Management Journal, 18(3), pp. 246-258.

Loch, C., Meyer, A. d., Pich, M. T. and Wiley, I. (2006) Managing the Unknown: a new approach to managing high uncertainty and risk in projects. Hoboken, N.J: John Wiley.

Loch, C., Mihm, J. and Huchzermeier, A. (2003) 'Concurrent Engineering and Design Oscillations in Complex Engineering Projects', Concurrent Engineering, 11(3), pp. 187-199.

Loch, C., Terwiesch, C. and Thomke, S. (2001) 'Parallel and sequential testing of design alternatives', Management Science, 5, pp. 663-678.

Loch, C. H., Solt, M. E. and Bailey, E. M. (2008) 'Diagnosing Unforeseeable Uncertainty in a New Venture*', Journal of Product Innovation Management, 25(1), pp. 28-46.

Loch, C. H. and Terwiesch, C. (1998) 'Communication and Uncertainty in Concurrent Engineering', Management Science, 44(8), pp. 1032-1048.

Luger, G. F. (2009) Artificial intelligence: structures and strategies for complex problem solving. 6th ed. edn. Boston; London: Pearson Addison-Wesley.

Mackenzie, N., and Knipe, S. (2006) ‘Research dilemmas: Paradigms, methods and methodology’, Issues in Educational Research, 16, pp. 193-205.

M., E. C. S. (2010) 'What is a Process Model? Reflections on the epistemology of design process models', in Heisig, P., P.J., C. and S., V. (eds.) Modelling and Management of Engineering Processes. New York: Springer, pp. 3-15.

Maher, M., Poon, J. and Boulanger, S. (1996) 'Formalising Design Exploration as Co-Evolution', in Gero, J. and Sudweeks, F. (eds.) Advances in Formal Design Methods for CAD IFIP — The International Federation for Information Processing: Springer US, pp. 3-30.

Malone, T. W. and Crowston, K. (1990) 'What is coordination theory and how can it help design cooperative work systems?', Proceedings of ACM conference on Computer-supported cooperative work, Los Angeles, California, USA., ACM, 7-10 October, pp.357-370.

Markus, T. A. (1969) 'The role of building performance measurement and appraisal in design method', in Broadbent, G. and Ward, A. (eds.) Design methods in Architecture. London: Lund Humphries.

Marston, M., Mistree, F. and Woodruff, G. W. (1997) 'A Decision-Based Foundation for Systems Design: A Conceptual Exposition'. CIRP International Design Seminar Proceedings on Multimedia Technologies for Collaborative Design and Manufacturing, University of Southern California, Los Angeles, October 9-10, 1-11.

Maver, T. W. (1970) 'Appraisal in the building design process.’ Emerging Methods in Environmental Design and Planning.

McCarthy, I. (2003) 'Technology management – A complex adaptive systems approach', INTERNATIONAL JOURNAL OF TECHNOLOGY MANAGEMENT, 25(8), pp. 728-745.

McConnell, S. (1996) Rapid development: taming wild software schedules. Redmond, Wash.; [Great Britain]: Microsoft Press.

McGrath, R. G. (2001) 'Exploratory Learning, Innovative Capacity and Managerial Oversight', The Academy of Management Journal, 44(1), pp. 118-131.

Meggs, P. B. (1992) A history of graphic design. 1st ed. edn. New York: Van Nostrand Reinhold.

Menezes, A. and Lawson, B. (2006) 'How designers perceive sketches', Design Studies, 27(5), pp. 571-585.

Meredith, J. (1998) 'Building operations management theory through case and field research', Journal of Operations Management, 16(4), pp. 441-454.

Mihm, J., Loch, C. and Huchzermeier, A. (2003) 'Problem-Solving Oscillations in Complex Engineering Projects', Management Science, 49(6), pp. 733-750.

Miles, M. B. and Huberman, A. M. (1994) Qualitative data analysis: an expanded sourcebook. 2nd ed. edn. Thousand Oaks, Calif.; London: Sage.

Miller, R. and Lessard, D. (2000) The Strategic Management of Large Engineering Projects: Shaping Institutions, Risks and Governance. Cambridge, MA.: MIT Press.

Mistree, F., Smith, W. F., Bras, B. A., Allen, J. K. and D., M. (1990) 'Decision-Based Design: A Contemporary Paradigm for Ship Design ', Annual Meeting of the Society Of Naval Architects And Marine Engineers, San Francisco, California, 31 October - 3 November, pp.565-597.

Montuori, A. (2003) 'From strategic planning to strategic design: reconceptualizing the future of strategy in organizations', World Futures, 59(3).

Mostow, J. (1985) 'Toward Better Models of The Design Process', THE AI MAGAZINE, 6(1).

Motortradesinsight (2013a) INTERVIEW: automotive designer David Hilton, Motorcity Europe founder and former Head of Exterior Design for Bentley. Available at: http://www.motortradesinsight.co.uk/article_page.asp?id=705&topic=interview-automotive-designer-david-hilton-motorcity-europe-founder-and-former-head-of-exterior-design-for-bentley (Accessed).

Motortradesinsight (2013b) INTERVIEW: Ernst Reim, Chief Interior Designer for Ford of Europe reveals how future looks more 'premium'. Available at: http://www.motortradesinsight.co.uk/article_page.asp?id=707&topic=interview-ernst-reim-chief-interior-designer-for-ford-of-europe-reveals-how-future-looks-more-premium (Accessed: 14/12/2017).

Muench, D. (1994) The Sybase Development Framework. Oakland, CA: Sybase Inc.

Nahm, Y.-E. and Ishikawa, H. (2004) 'Integrated Product and Process Modelling for Collaborative Design Environment', Concurrent Engineering, 12(1), pp. 5-23.

Nelson, R. A. (2000) 'Recent Evolutionary Theorizing About Economic Change', in Ortmann, G., Sydow, J. and Türk, K. (eds.) Theorien der Organisation: Die Rückkehr der Gesellschaft. Wiesbaden: VS Verlag für Sozialwissenschaften, pp. 81-123.

Newell, A. and A. Simon, H. (1976) 'Computer Science as Empirical Inquiry: Symbols and Search', Commun. ACM, 19, pp. 113-126.

Newell, A. and Simon, H. A. (1972) Human problem solving. Englewood Cliffs, N.J.: Prentice-Hall.

Nieuwenhuis, J. (2007) 'Qualitative research designs and data gathering techniques', in Maree, K. (ed.) First Steps in Research. Pretoria: pp. 70-92. Pretoria: Van Schaik Publishers, pp. 70-92.

Osborne, S. M. (1993) Product development cycle time characterization through modelling of process iteration. MIT [Online] Available at: http://hdl.handle.net/1721.1/12381 (Accessed: 11/03/2014)

Otto, K. N. and Antonsson, E. K. (1991) 'Trade-off strategies in engineering design', Research in Engineering Design, 3(2), pp. 87-103.

O'Donovan, B. D., Clarkson, P. J. and Eckert, C. '(2003), Signposting: modelling uncertainty in design processes, Proceedings of the 14th International Conference on Engineering Design (ICED03), 19-21 August, Stockholm, Sweden.

O'Donovan, B. D., Clarkson, P. J. and Eckert, C. (2004) ' Simulating design processes to assist design process planning'. Proceeding of the ASME Design Engineering Technical Conference (DETC04), Salt Lake City, UT, 28 September - 2 October.

Page, S. E. (1996) 'Two measures of difficulty', Economic Theory, 8(2), pp. 321-346.

Pahl, G., Beitz, W. and Wallace, K. (1996) Engineering design: a systematic approach. 2nd ed. edn. London: Springer.

Patton, M. Q. (2002) *Qualitative research and evaluation methods*. 3rd edn. Thousand Oaks, Calif ; London: Sage.

Person, O., Snelders, D., Karjalainen, T.-M., & Schoormans, J. P. (2007). Complementing intuition: Insights on styling as a strategic tool. Journal of Marketing Management, 23(9 & 10), 901–916.

Pettigrew, A. M. (1990) 'Longitudinal Field Research on Change: Theory and Practice', Organization Science, 1(3), pp. 267-292.

Peña, W. and Parshall, S. (1969) Problem seeking: an architectural programming primer. 1st ed. edn. Hoboken, N.J.: John Wiley & Sons.

Pfitzer, S. and Rudolph, S. (2007) 'Re-Engineering Exterior Design: Generation of Cars by Means of a Formal Graph-Based Engineering Design Language', International Conference on Engineering Design, Cité Des Sciences Et De L'industrie, Paris, France, 28 - 31 August.

Pich, M., Loch, C. and De Meyer, A. (2002a) 'On Uncertainty, Ambiguity, and Complexity in Project Management', Management Science, 48, pp. 1008-1023.

Pieroni, E. (2006) ' Integrating Project Management, Concurrent Engineering, and Engineering Design to Improve Ship Design'. The 3rd International Conference on Production Research (ICPR- AM06), Curitiba, Brazil, 30 July - 2 August.

Piirainen, K., Gonzalez, R. A. and Kolfschoten, G. (2010) 'Quo Vadis, Design Science? – A Survey of Literature', in Winter, R., Zhao, J.L. and Aier, S. (eds.) Global Perspectives on Design Science Research: 5th International Conference, DESRIST 2010, St. Gallen, Switzerland, June 4-5, 2010. Proceedings. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 93-108.

Popper, K. R. (2002) The logic of scientific discovery. London: Routledge.

Prasad, B. (1996) Concurrent Engineering Fundamentals, Vol I: Integrated Product and Process Organization. NJ: Prentice Hall PTR.

Psychology Wiki, Holism (n.d.), Available at: https://psychology.fandom.com/wiki/Holism (Accessed: 22/04/2019)

Punch, K. (2005) Introduction to social research: quantitative and qualitative approaches. 2nd ed. edn. London: SAGE.

Rizal., S. (2005) 'The Interface between Design and Management', Design Issues, 21(1), pp. 81-93, doi:10.1162/0747936053103020

Reddy, J. M., Finger, S., Konda, S. and Subrahmanian, E. (1998) 'Design as Building and Reusing Artifact Theories: Understanding and Supporting Growth of Design Knowledge', in Duffy, A.H.B. (ed.) The Design Productivity Debate. London: Springer London, pp. 268-290.

Reich, Y. (1995) 'A critical review of General Design Theory', Research in Engineering Design, 7(1), pp. 1-18.

Reidys, C. M. and Stadler, P. F. (2002) 'Combinatorial Landscapes', SIAM Review, 44(1), pp. 3-54.

Reitman, W. (1964) 'Heuristic decision procedures, open constraints, and the structure of ill-

defined problems ', in Shelly, M.W. and G.L., B. (eds.) Human judgments and optimality. New York John Wiley and Sons, pp. 282–315

Restrepo, J. and Christiaans, H. (2004) 'Problem Structuring and Information Access in Design', Journal of Design Research (JDR), 4(2), pp. 218-236.

Rigelsford, J. (1999) 'Concurrent Engineering Fundamentals Volumes 1 & 2', Assembly Automation, B. PrasadPrentice-Hall.

Rittel, H. W. J. and Webber, M. M. (1973) 'Dilemmas in a general theory of planning', Policy Sciences, 4(2), pp. 155-169.

Rivkin, J. W. (2000) 'Imitation of Complex Strategies', Management Science, 46(6), pp. 824-844.

Khandani, S. (2005) Engineering Design Process: Education Transfer Plan. Available at: https://www.studocu.com/row/document/technical-university-of-kenya/engineering/me101-4-engineering-design-process/35967977 (Accessed: 02/10/19).

Schon, D. A. and Wiggins, G. (1992) 'Kinds of seeing and their functions in designing', Design Studies, 13(2), pp. 135-156.

Schon, D. A. (1990) Educating the reflective practitioner. 4th ed. edn. San Francisco, CA: Jossey-Bass, p. 376.

Schön, D. A. (1983) The reflective practitioner: how professionals think in action. Aldershot: Avebury.

Sharafi, A., Wolfenstetter, T., Wolf, P. and Krcmar, H. (2010) 'Comparing product development models to identify process coverage and current gaps: A literature review'. IEEE International Conference on Industrial Engineering and Engineering Management, 7-10 Dec. pp.1732-1736.

Siggelkow, N., & Rivkin, J. W. (2005). Speed and Search: Designing Organizations for Turbulence and Complexity. Organization Science, 16(2), pp.101–122. http://www.jstor.org/stable/25145954

Simon, H. A. (1956) 'Rational choice and the structure of the environment, Psychological Review, 63(2), pp. 129-38.

Simon, H. A. (1957) Models of Man, social and rational. Mathematical essays on rational human behaviour in a social setting. New York: John Wiley & Sons.

Simon, H. A. (1962) 'The Architecture of Complexity', Proceedings of the American Philosophical Society, 106(6), pp. 467-482.

Simon, H. A. (1973) 'The structure of ill structured problems', Artificial Intelligence, 4(3), pp. 181-201.

Simon, H. A. (1981) The sciences of the artificial. 2nd ed. edn. Cambridge, Mass. ; London: MIT Press.

Simon, H. A. (1995) 'Problem forming, problem finding, and problem solving in design', in Collen, A. and Gasparski, W., W. (eds.) Design and systems: General applications of methodology. Brunswick, NJ: Transaction Publishers, pp. 245-257.

Simon, H. A. (1996) The sciences of the artificial. 3rd ed. edn. Cambridge, Mass.; London: MIT Press.

Simon, H. A. (2000) 'Bounded rationality in social science: Today and tomorrow', Mind & Society, 1(1), pp. 25-39.

Simon, H. A. and Newell, A. (1971) 'Human problem solving: The state of the theory in 1970', American Psychologist, 26(2), pp. 145-159.

Smith, P. G. and Reinertsen, D. G. (1992) 'Shortening the Product Development Cycle', Research Technology Management, 35(3), pp. 44-49.

Smith, R. P. and Eppinger., S.D. (1993) 'Characteristics and models of iteration in engineering design. '. Proceedings of the 9th International Conference on Engineering Design (ICED 93), August 17-19, Zurich, Netherlands, pp. 564-571.

Smith, R. P. and Morrow, J. A. (1999) 'Product development process modelling', Design Studies, 20(3), pp. 237-261.

Smyth, S.N. and Wallace, D. R. (2000) ‘Towards The Synthesis of Aesthetic Product Form' Proceedings of the ASME 2000 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Baltimore, Maryland, September 10-13, pp. 113-120.

Stacey, M. K. and Eckert, C. M. (2010) 'Reshaping the box: creative designing as constraint satisfaction', International Journal of Product Development, 11(3/4), pp. 241-255.

Steadman, P. (1979) 'The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts, Cambridge, UK: Cambridge University Press, 1979

Strauss, A. L. and Corbin, J. M. (1998) Basics of qualitative research: techniques and procedures for developing grounded theory. 2nd ed. edn. Thousand Oaks, Calif.: Sage Publications.

Suh, N. P. (1990) The principles of design. New York ; Oxford: Oxford University Press.

Suh, N. P. (2001) Axiomatic design: advances and applications. New York: Oxford University Press.

Tate D. and Nordlund M., (1996) 'A design process roadmap as a general tool for structuring

and supporting design activities', Proceedings of the Second World Conference on Integrated Design and Process Technology (IDPT), Society for Design and Process Science, Austin, TX, pp 97-104.

Terwiesch, C., C. H. Loch, and Niederkofler M. (1996) 'Managing uncertainty in concurrent engineering'. 3rd Internat.ional EIASM Conferance, Fontainebleau, France, pp. 693–706.

Thagard, P. (1996) Mind: introduction to cognitive science. Cambridge, Mass.; London: MIT Press.

Thanasegaran, G. 'Reliability and Validity Issues in Research'.

Thayer, J. T., Stern, R. and Lelis, L. H. S. (2012) 'Are We There Yet? -Estimating Search Progress.'. Fifth Annual Symposium on Combinatorial Search, Niagara Falls, Canada, 19-21 July 21.

Thomke, S. H. (1998) 'Managing Experimentation in the Design of New Products', Management Science, 44(6), pp. 743-762.

Thompson, S. C. (2011) Rational design theory: a decision-based foundation for studying design methods. Georgia Tech [Online] Available at: http://hdl.handle.net/1853/39490 (Accessed: 06/09/2016)

Thurston, D. L. (2001) 'Real and misconceived limitations to decision based design with utility analysis', Journal of Mechanical Design, Transactions of the ASME, 123(2), pp. 176-182.

Todd, P. M., Hills, T. T. and Robbins, T. W. (2012) Cognitive search: evolution, algorithms, and the brain. Strüngmann Forum reports. Cambridge, MA: MIT Press.

Tolba, R. and Mushtaha, A. (2008) 'Integrating V-Model into the Web Development Process', the International Arab Conference on e-Technology (IACeT), Amman, Jordan, October 15-16.

Tomiyama, T. (1994) 'From general design theory to knowledge-intensive engineering', Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 8(4), pp. 319-333.

Tomiyama, T. and Yoshikawa, H. (1986) Extended General Design Theory (2nd Report).

Tovey, M. (2002) 'Concept design CAD for the automotive industry', Journal of Engineering Design, 13(1), pp. 5-18.

Tsai, L. W., Schultz, G. and Higuchi, N. (2000) 'A Novel Parallel Hybrid Transmission', Journal of Mechanical Design, 123(2), pp. 161-168.

Tsichritzis, T. C. and Lochovsky, F. H. (1997) Data base management systems. New York: Academic Press.

Tversky, A. and Kahneman, D. (1986), Rational Choice and the Framing of Decisions, The

Journal of Business, 59(4), pp S251–S278: http://www.jstor.org/stable/2352759

Ulrich, K. (1995) 'The role of product architecture in the manufacturing firm', Research Policy, 24(3), pp. 419-440.

Ulrich, K. T. (2011) Design: creation of artifacts in society. University of Pennsylvania.

Ulrich, K. T. and Ellison, D. J. (1999) 'Holistic Customer Requirements and the Design-Select Decision', Management Science, 45(5), pp. 641-658.

Ulrich, K. T. and Eppinger, S. D. (2007) Product design and development. 4th ed. edn. New York: McGraw-Hill Higher Education; London: McGraw-Hill [distributor].

Unger, D. W. and D., E. S. (2009) 'Comparing product development processes and managing risk', International Journal of Product Development, 8(4), pp. 383-402.

Van der Ryn, S. (1966) 'Problem and Puzzles: Searching for a Science of Design', AIA Journal, 45(1), pp. 37-42.

Vanlehn, K. (1988) Problem Solving and Cognitive Skill Acquisition in Foundations of Cognitive Science,. Cambridge, MA: MIT Press, p. Foundations of Cognitive Science,.

Von Neumann, J. and Morgenstern, O. (1947) Theory of games and economic behaviour. [S.l.]: Princeton University Press.

Voss, C., Tsikriktsis, N. and Frohlich, M. (2002), "Case research in operations management", International Journal of Operations & Production Management, Vol. 22 No. 2, pp. 195-219. https://doi.org/10.1108/01443570210414329

Wang, J., Lin, W. and Huang, Y.-H. (2010) 'A performance-oriented risk management framework for innovative R&D projects', Technovation, 30(11), pp. 601-611.

Wang, Y. and Chiew, V. (2010) 'On the cognitive process of human problem solving', Cognitive Systems Research, 11(1), pp. 81-92.

Wassenaar, H. J. and Chen, W. (2003) 'An Approach to Decision-Based Design with Discrete Choice Analysis for Demand Modelling', Journal of Mechanical Design, 125(3), pp. 490-497.

Weber, J. (2009) 'Primary or Customer Relevant Complete Vehicle Characteristics', Automotive Development Processes: Springer Berlin Heidelberg, pp. 107-286.

Weick, K. E. and Sutcliffe, K. M. (2001) Managing the unexpected: assuring high performance in an age of complexity. 1st ed. edn. San Francisco: Jossey-Bass.

Weinberger, E. D. (1991) 'Local properties of Kauffman's NK model: A tunably rugged energy landscape', Physical Review A, 44(10), pp. 6399-6413.

Whitney, D. E. (1990) 'Designing the design process', Research in Engineering Design, 2(1), pp. 3-13.

Wilke, A., Hutchinson, J. M. C. and Todd, P. M. (2009) 'Fishing for the right words: decision rules for human foraging behaviour in internal search tasks.' Cognitive Science, 33(3), pp. 497-529.

Willaert, S. S. A., de Graaf, R. and Minderhoud, S. (1998) 'Collaborative engineering: A case study of Concurrent Engineering in a wider context', Journal of Engineering and Technology Management, 15(1), pp. 87-109.

Williams, T., Eden, C., Ackermann, F. and Tait, A. (1995) 'The Effects of Design Changes and Delays on Project Costs', Journal of the Operational Research Society, 46(7), pp. 809-818.

Wilson, D. S. (1988) 'Holism and Reductionism in Evolutionary Ecology', Oikos, 53(2), pp. 269-273.

Wright, S. (1932) ' The roles of mutation, inbreeding, crossbreeding and selection in evolution'. Proceedings of the sixth international congress of genetics,8, pp. 209-232.

Wynn, D. and Clarkson, J. P. (2005) 'Models of designing', in Clarkson, J. and Eckert, C. (eds.) Design process improvement: A review of current practice. London: Springer, pp. 24-59.

Wynn, D., Eckert, C. and Clarkson, P. J. (2007) 'Modelling iteration in engineering design'. Proceedings of ICED 2007, the 16th International Conference on Engineering Design, 28-31 August, Paris, France.

Wynn, D. C. and Clarkson, P. J. (2018) 'Process models in design and development', Research in Engineering Design, 29, pp. 161-202.

Yassine, A. (2004) 'An Introduction to Modelling and Analyzing Complex Product Development Processes Using the Design Structure Matrix (DSM) Method', Quaderni di Management (Italian Management Review), 9, pp. 1-17.

Yassine, A. A., Chelst, K. R. and Falkenburg, D. R. (1999) 'A decision analytic framework for evaluating concurrent engineering', IEEE Transactions on Engineering Management, 46(2), pp. 144-157.

Yazdani, B., and Holmes, C.K. (1999) ‘Four Models of Design Definition: Sequential, Design Centered, Concurrent and Dynamic’, Journal of Engineering Design, 10, pp. 25-37.

Yin, R. K. (1994) Case Study Research: Design and Methods. 2Rev.ed. edn.: Thousand Oaks Calif: Sage Publications.

Yoshikawa, H. (1981) 'General Design Theory and a CAD system', Man-Machine Communication In CAD/CAM', Proceedings of the IFIP WG5.2-53 Working Conference, North-Holland, Amsterdam, pp. 35-57.

Zangwill, W. I. (1992) 'Concurrent Engineering: Concepts and Implementation', IEEE Engineering Management Review, 20, pp. 4-52.

Zu, X. and Huang, H.-Z. (2004) Research on product development process modelling, the 8th International Conference on Computer Supported Cooperative Work in Design Proceedings, Xiamen, China, 26-28 May 2004. 2, pp. 33-38.