A Conceptual System Design and Managerial Complexity Competency Model

A thesis submitted for the degree of Doctor of Philosophy

by

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December 2013

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DECLARATION

As required under the University's regulations, I hereby declare that this thesis is not substantially the same as any that I have submitted or will be submitting for a degree or diploma or other qualification at this or any other university. Furthermore, this thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specified explicitly in the text.

ABSTRACT

Complex adaptive systems are usually difficult to design and control. There are several particular methods for coping with complexity, but there is no general approach to build complex adaptive systems. The challenges of designing complex adaptive systems in a highly dynamic world drive the need for anticipatory capacity within engineering organizations, with a goal of enabling the design of systems that can cope with an unpredictable environment. This thesis explores this question of enhancing anticipatory capacity through the study of a complex adaptive system design methodology and complexity management competencies. A general introduction to challenges and issues in complex adaptive systems design is given, since a good understanding of the industrial context is considered necessary in order to avoid oversimplification of the problem, neglecting certain important factors and being unaware of important influences and relationships. In addition, a general introduction to complex thinking is given, since designing complex adaptive systems requires a non-classical thought, while practical notions of complexity theory and design are put forward. Building on these, the research proposes a Complex Systems Life-Cycle Understanding and Design (CXLUD) methodology to aid system architects and engineers in the design and control of complex adaptive systems. Starting from a creative anticipation construct - a loosening mechanism to allow for more options to be considered, the methodology proposes a conceptual framework and a series of stages to follow to find proper mechanisms that will promote elements to desired solutions by actively interacting among themselves. To illustrate the methodology, a financial systemic risks infrastructure systems architecture development case study is presented. The final part of this thesis develops a conceptual model to analyse managerial complexity competency model from a qualitative phenomenological study perspective. The model developed in this research is called Understanding-Perception-Action (UPA) managerial complexity competency model. The results of this competency model can be used to help ease project manager’s transition into complex adaptive projects, as well as serve as a foundation to launch qualitative and quantitative research into this area of project complexity management.

DEDICATION

For Jennifer and my precious children, Chigozie, Chisom and Chidinma

ACKNOWLEDGEMENTS

During the four years of my studies as doctoral student I have been given the opportunity to gain knowledge and share experiences with many people. They have contributed to shape my thoughts as a researcher and as a person. It is a pleasure now to convey my gratitude to them all. First of all, I owe a special thanks to Dr Steve Counsell for his constant support, unflinching encouragement and guidance from the very early stages of this research. Steve served as my supervisor and helped me with the most critical steps of my life as a PhD student. Thank you for all the time and resources you have dedicated me, for reviewing several versions of my papers and last, of the thesis. The traits I possess that have allowed me to complete this work; the desire to learn, the interest in the world around me, the confidence, the ability and desire to work hard and persevere and the humility to be taught are thanks to the great parents and aunt I have. The most important thank you goes to my family for believing in me more than I did myself. Thanks to my dear Mom, for actively supporting and encouraging my decisions, for understanding and knowing my silent thoughts and forgiving my absences. Special thanks goes to my late aunt “Awube Nwanyi” - whose spirit and teaching have taught me the patience and skills necessary for approaching and solving most problems I face. Thanks to my dear Jennifer. She has worked every bit as hard as I have, she has felt the stress and she has shared the disappointments and the successes along with me. More significantly, however, she has been a strong strength to our family. The most important and lasting work we will do are in our home and Jennifer made sure that work continued uninterrupted. She carried her own load as a professional, a wife and a mother and then took on much of mine! Finally, I acknowledge the help of my Heavenly Father, from whom all knowledge flows and who is the fount of every blessing. He has truly blessed me and my family.

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CHAPTER 1 INTRODUCTION

In this chapter, an introduction of the thesis is given. The introduction is organised as follows. In Section 1.1, the context of the thesis is discussed with regards to understanding the main focus of the research. In Section 1.2, we introduce the motivation of the thesis in order to focus our approach to thesis development. In Section 1.3, the main research questions and the objectives of the thesis are presented, which are then followed with an overview of the research process of the thesis in Section 1.4. In Section 1.5, we use a hierarchy of method impacts on the systems design and management decision maker to further define the scope of the thesis, followed with a summary of the expected theoretical and practical contributions of this thesis (Section 1.6). Finally, the thesis outline is listed in Section 1.7.

1.1 Context

1.1.1 Research Focus

This thesis finds its best fit within the area of complex adaptive systems design and control research. Almost all the critical problems of our time are problems of control and almost all of them concern complex adaptive systems. Complex adaptive systems have either explicitly or implicitly been the subject of research in different scientific fields applying a wide range of applications. There is no general definition of complex adaptive system, since the construct achieves different meanings in different contexts. Still, we can say that a system is complex adaptive if it consists of several elements interacting to exchange information. The system as a whole has emergent properties that cannot be understood by reference to the component parts (Barnes et al., 2003) and the elements are difficult to separate. This difficulty arises from the interactions between elements (Gershenson and Heylighen, 2005). According to Simon (1996), most complex [adaptive] systems can often be described by a hierarchy; redundant components can be grouped together and considered as integrated units. One can also view complex adaptive systems in terms of properties that are often true for such systems (Berryman and Campbell, 2010), such as nonlinearity, self-organisation, feedback loops, adaptability, evolvability, flexibility and diversity.

Our current society is highly dependent, both socially and economically, on well-functioning complex adaptive systems. However, these systems are increasingly difficult to design and manage (Gershenson, 2007). The field of complexity research explores the characteristics and evolution of such systems, and seeks to explain their apparently motivated nature. There, researchers from mathematics, computing, the physical and social sciences were drawn together in an attempt to synthesise new ways of understanding complex adaptive systems (Waldrop, 1992; Lewin, 1999). Complexity theory has therefore always occupied an inter-disciplinary space. Complex adaptive systems research is distinguished by particular emphasis on (1) inter-disciplinary methods which span technology, management, and policy; (2) temporal system properties, commonly referred to as the “ilities”; (3) the interconnectedness of product systems with the enterprises that develop and sustain them and (4) value stream complexities arising from stakeholder heterogeneity.

Complex adaptive systems can be technical (engineered), biological, social or some combination. Examples of complex adaptive systems are biological systems, the Internet, computer networks, public health systems, water supply systems, banking and finance systems, engineering organisations that developed and support specific systems and the electric power grid.

The boundaries of complex adaptive systems are frequently indistinct and often a matter of particular descriptions of those systems (Manson, 2001). Thus, design and control of complex adaptive systems often, if not always, occurs in a context that is uncertain - its needs change, technology evolves and resources are uncertain. Many decisions routinely made are dynamic in nature - a number of decisions are required rather than a single decision, decisions are interdependent and the environment in which a decision is set changes over time. Such a challenging environment thus results in high ambiguity. To cope with a complex environment, organisations must access and evaluate a constantly evolving, multifaceted view of the operational context since the timing and knowledge of external events will be critical.

The expectation for a system to continue to deliver stakeholder value in the face of changing contexts and needs (or an involuntary change to the design space) drives the need for enhancing anticipatory capacity within complex systems engineering organisations. To continue to design and manage valuable systems requires engineering organisations to constantly access up-to-date information, methods and knowledge. The evolution of anticipatory capacity can be viewed from at least two perspectives (Rhodes and Ross, 2009): *enhancing competencies in the engineering organisation and design methods used.* These two key elements are the focus of the research program carried out and the results presented in this thesis. A process supporting the relationships between the key challenges, drivers and the focus of this thesis is shown in Figure 1-1. Strong increases in the complexity and perishability of systems are the major drivers for continuous research into new design methods and enhanced engineering abilities. Anticipatory capacity concepts are formulated to create and manage systems that deliver desired capabilities, but taking implementable form in a design methodology and enhanced engineering abilities.

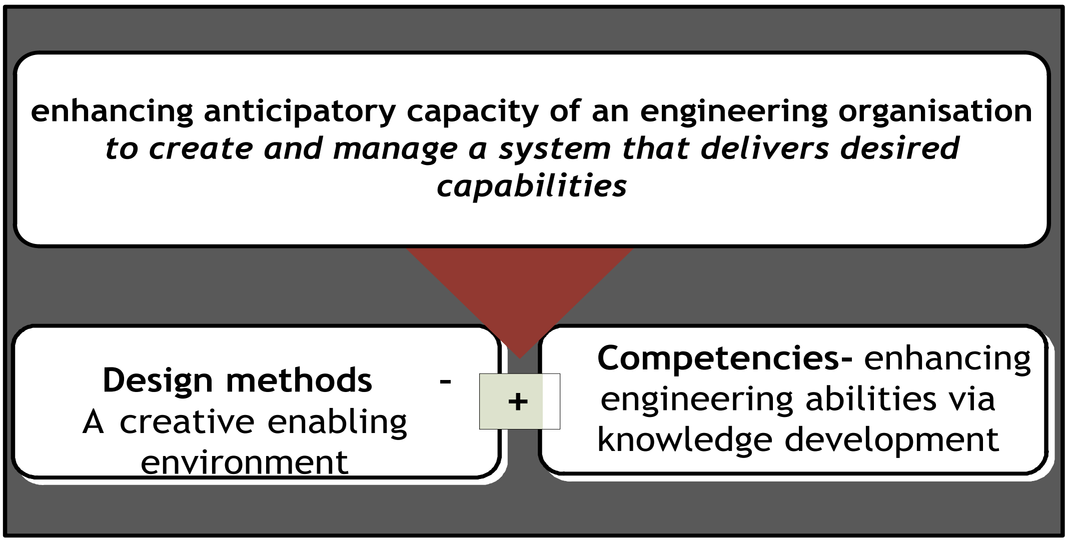

Figure 1-1: Principal activities of this thesis focus (Source: Author)

Therefore, this thesis has the focus of contributing to an enhanced anticipatory capacity of a complex adaptive system engineering organisation at the level of conceptual design. It does this primarily by exploring, understanding, characterising, analysing and defining a new approach to developing systems; secondly, by identifying skills, abilities and expertise that project managers are required to draw upon to successfully cope with managerial complexity.

1.1.2 Conceptual Design

Within complex adaptive systems engineering, the research focuses on the application of a creative approach to conceptual design, knowledge capture and synthesis. By creative approach, we imply that we are attempting to advance towards an outcome that is new, unstructured and open-ended.

According to Ulrich and Eppinger (2004), conceptual design includes both concept development (i.e., identification of stakeholders, enumeration and evaluation of design alternatives, and selection of one or more concepts for further development) and system-level design (i.e., definition of the architecture, including subsystem decompositions and functional specifications). Empirical evidence suggests that the lifecycle value delivered by systems is primarily determined at the beginning of development programs, highlighting the criticality of good decision-making during conceptual design (Richards, 2009). Thus, conceptual design requires careful consideration, as these decisions will have significant influence on system lifetime performance and are often made with incomplete system knowledge. Good conceptual design means innovation and, according to (Perkins, 1981), an innovative design comes about when one deliberately tries to create one.

The topics of interest imply that the main perspective adopted in this thesis is an engineering one, concerned with methods and knowledge development with the purpose of being of practical applicability. The selection of the research topic and formulation of the research questions are the foundations of any meaningful research. A researcher's interests naturally affect the initial selection of the research area and topic. In Benbasat and Zmud (1999) a suggestion was made that to avoid lack of relevance in the results of research work, certain factors should be considered when selecting a research topic and its objectives. In making decisions on the thesis' research topic and research areas, the following factors adapted from Benbast and Zmud (1999) were considered:

- Interesting – the research should address the problems and challenges of concern to practitioners and researchers alike.
- Applicable – the knowledge and results should be useful to practitioners.
- Current – the topic should be current at the time of publication of the results.
- Accessible – the results should be expressed in a style and format which makes the results understandable by practitioners and researchers alike.

From the perspective of the research topic, complex adaptive systems, challenges of systems architecting, systems design methods, managerial complexity and competency models are all current topics and research relevant for practitioners and academia. These can be verified by the number of international conferences and journals dedicated to these subjects.

1.2 Motivation

1.2.1 Design Methods Research

Complex adaptive systems can be engineered, biological, social or some combination. Complex adaptive systems are usually difficult to model, design and control. An important characteristic of complex adaptive systems is that they are in some sense purposive. This means that the dynamics of the system have a definable objective or function (Bagdasaryan, 2008). Continuous research on complex adaptive systems is a recognised need (Strogatz, 2001). Insights from literature indicate that there are different inter-related approaches to the modern study of complex adaptive systems, but compiling views of different authors (Bagdasaryan, 2008) suggests that an effective approach has to follow the principles of systems analysis, summarised as:

1. Description of the system. Identification of its main properties and parameters;
2. Study of inter-connections amongst parts of the system, which include informational, physical, dynamical, temporal interactions, as well as functionality of parts within the system;
3. Study of the system interactions with its environment; in other words, with other systems, nature, etc.
4. System decomposition and partitioning. Decomposition supposes the extraction of a series of system parts and partitioning suggests the extraction of parallel system parts. These methods can be based on cluster analysis (iterative process of integration of system elements into groups) or content analysis (system division into parts, based on physical partitioning or function analysis);
5. Study of each subsystem or system part, utilizing optimal corresponding tools (multidisciplinary approaches, problem-solving methods, expert advice, knowledge discovery tools, etc.).
6. Integration of the results received from the previous stage and obtaining a pool of fused knowledge about the system.

Value complex adaptive system design includes 1) the definition of objectives and their ordering in a hierarchical structure; 2) determining the relations between objectives and practical constraints and 3) the definition of the metrics that determine the attainment of the objectives (Sage and Rouse, 1999). According to Baum et al., (1998) a system's architecture can serve as the complete picture for integrating these different aspects. According to Crawley and Weigel (2004), every system has architecture, whether deliberately generated as part of the design process or the result of accretion or other less directed processes spread out over time. Thus, architectures are said to allow or preclude nearly all of the attributes of a system.

The purpose of any system is to provide some level of value to the stakeholders of that system. Stakeholders also have some level of expectation on system performance when exposed to perturbations. As complex adaptive systems progress through changing contexts and needs, their performance may exceed or dip below stakeholder expected values. The idea of value robustness (e.g., de Weck et al., 2012; Ross and Rhodes, 2008a) is to maintain value delivery despite these changes in contexts and needs. A complex adaptive system can change; it can remain robust, or may be versatile to meet stakeholder expectations in response to changing contexts and needs. Therefore, the three strategies that systems designers may use to achieve value robustness would be those that facilitate changeability, robustness and/or versatility. This thesis focuses on a conceptual design methodology for systems that intentionally change – changeability. Methods of responding to perturbations can be considered as either passive or active. Active responses are those where there is an agent that observes orients, decides and acts. Passive responses, on the other hand, have no agent that is intelligently making a decision—the system responds according to the laws of physics, with predicable cause-effect relationships.

According to (Roos, 1998), new approaches, frameworks and theories need to be developed to better understand engineering systems design. In addition, success in design according to some authors (e.g., Eckert et al., 2010) is more likely if designers and design managers are aware of: models of design that can be used to describe the design process, perspectives on design from which to view the design process, good design practice to improve product and process performance and a range of approaches to ensure effective and efficient design management.

1.2.2 Developing Managerial Complexity Competencies

According to (Rhodes and Ross, 2009), anticipatory capacity is the capacity of an organization to continuously develop and apply knowledge acquired through a structured approach to anticipate changing scenarios as needs and context change over time. The challenges of designing complex systems in a highly dynamic world (Rhodes and Ross, 2009) and increased perishability of fielded systems (both obsolescence and technology refresh rates) drive the need for anticipatory capacity in engineering organisations.

Insights from literature indicate the needs for more research in knowledge capture and synthesis of anticipatory capacity enablement. Elements which enable anticipatory capacity of an engineering organization include the existence of appropriate dynamic systems competencies in the workforce, such as understanding the environmental context in which decisions are made and development of methods for decision-making in the design of systems (Rhodes and Ross, 2009).Empirical research indicates that managerial complexity is a major cause of numerous reported failures in system design as well as operational failures. According to Levin and Ward (2011), the topic of the complexity of programs has not been specifically addressed in the rather meagre selection of books and publications on program management now available in the marketplace. Additionally, there is little, if any, information available today identifying a set of competencies a program manager needs to possess to successfully complete their program and deliver the benefits desired by stakeholders.

There is a gap in both academia and industry research communities on enhancing anticipatory capacity of complex adaptive systems engineering organisations. A project manager's primary tool is their mind (Hartman, 2008). Finding new ways to prepare the mind for effective project management is needed and the need for qualitative project managerial complexity research has been identified (Cicmil et al., 2006). Thus, the motivation for the proposed research includes the need to bring structure and discipline to the process of defining managerial complexity competency models.

1.3 Research Question and Objectives

From the general background provided by Sections 1.1 and 1.2, a number of aims and research objectives can be stated for the work in the present thesis. This research study has two main research questions and seven sub-research objectives. These are:

1. What is the best way to package a design method and process that can stimulate creativity and enable engineering of complex adaptive systems (architecture) in a heterogeneous, uncertain and changing context?
2. What are the relationships between complexity theories and project managers' perceptions of managerial complexity?

In order to address the research questions a number of research objectives were set:

1. To explain the research paradigm, methods and techniques that fit the current research questions and lead to the final artifacts developed in this research.
2. To explore and develop a conceptual framework describing patterns that enable a better understanding of complex systems.
3. To undertake a study to explore, describe and explain systems architecting challenges and issues facing complex systems architecting teams and

secondly, given the research need for enhancing anticipatory capacity of the architecting organization, utilise the findings to suggest a competency model.

4. Undertake a study to constructively create an organised design construct and enabling environment which stimulates creativity and innovation when bringing desired properties into system conceptual design.
5. Evaluate and validate objective 4 through real-life cases in regards to financial systemic risks infrastructure systems.
6. Undertake a study to explore how complex adaptive system project leaders perceive and describe the lived experiences of coping with managerial complexity.

1.4 A Summary of the Research Approach

To address the two research questions and the research objectives, the research methodology followed involves knowledge capture and synthesis, theory development, theory evaluation and case applications. Figure 1-2 depicts the relationships among these four general phases of the research process, where the arrows mean “lead to.” Each phase is not a discrete step in a serial process but rather one aspect of an iterative, concurrent process of continuous learning, revisiting of assumptions and development and testing of theory. The principal influences of the research process are constructivism and pragmatism, which required a qualitative research approach. The constructive approach is defined as a goal-directed practical problem solving activity through the construction of models, diagrams or plans. The constructive approach always aims at an attempt to demonstrate explicitly the practical usability of the solution. Constructive approach is also innovative by nature (Kasanen et al., 1993). The following paragraphs introduce Figure 1-2 with full description of the research methodology available in Chapter 3.

1. **Problem analysis and background studies:** Several areas related to the research objective were reviewed with regard to their possible contribution to complex adaptive systems architecture process development. A full discussion of the disciplines and fields of research investigated can be found in Chapter 2. This provides a context from which a plan of action was constructed based on the gathered knowledge.

2. Exploratory investigation: The commitment to focusing on the experiences of users of services implies a reliance on empirical evidence directly from those users. We investigate this to identify challenges and issues facing a complex adaptive systems architecting organisation. Knowledge about systems architecting practice was elicited from experts and practitioners using the Delphi technique.

3. Develop the CXLUD Framework as an organised design enabling environment which stimulates creativity and innovation for engineering organisations seeking to define value robustness into systems conceptual design. The approach emerges from the analysis of real industrial problems in combination with a theoretical investigation.

4. Provide a proof-of-concept to the viability of the CXLUD methodological environment as an effective systems conceptual design method. This objective will be achieved by applying the CXLUD approach to a selected industrial case study.

5. Provide an empirical substantiation of the goodness and completeness of the CXLUD approach. This objective will be achieved by eliciting feedback from industrial experts about the framework.

6. Development of a phenomenological informed managerial complexity competency model: The main idea of empirical phenomenology is that scientific explanation must be grounded in the first-order construction of the actors; that is their own meanings and words. A phenomenological study from the perspective of the systems architecting project managers was investigated to draw conclusions on how insights from complexity science can inform managerial complexity practice.

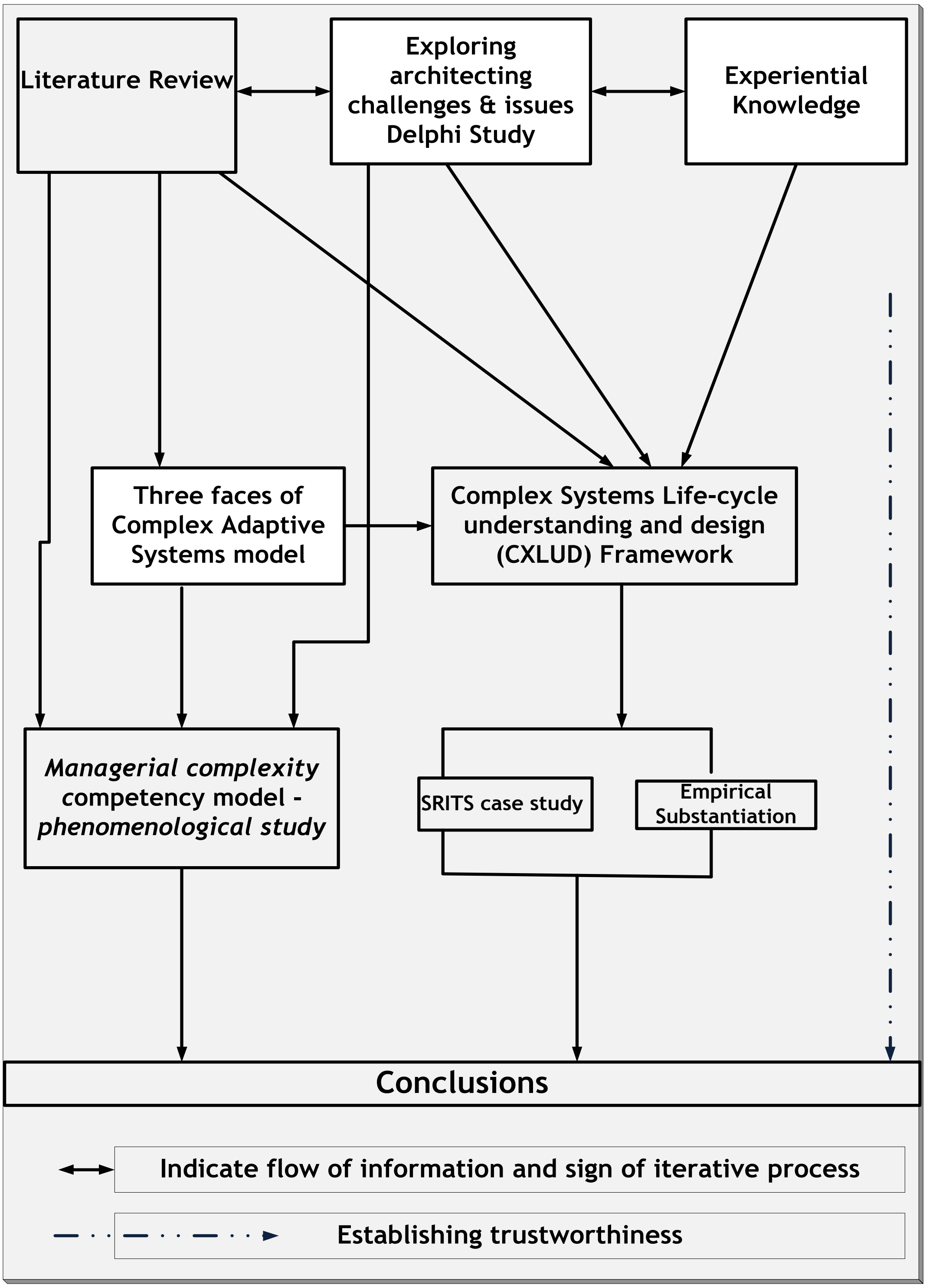

Figure 1-2: Diagram of thesis research process

1.5 Defining the Scope

The research questions and research objectives defined in Section 1.3 indicate the research scope. Another way of projecting the research scope is by creating a hierarchy of method impacts on the systems design and management decision maker. In this hierarchy as shown in Figure 1-3, a method has to produce knowledge/information which is scientifically sound (level 1). According to (Bots, 2003)**,** this level is associated with the knowledge generation process. Second, the information has to be well-understood (represented by level 2) by analysts, before it can be understood and accepted by policymakers (represented by level 3). Effectiveness on level 2 pre-supposes effectiveness on level 1 etc. The next level of impact will be when the recommendations based on the knowledge produced are acted upon (represented by level 4) and finally, policy actions to bring about desired results (represented by level 5).

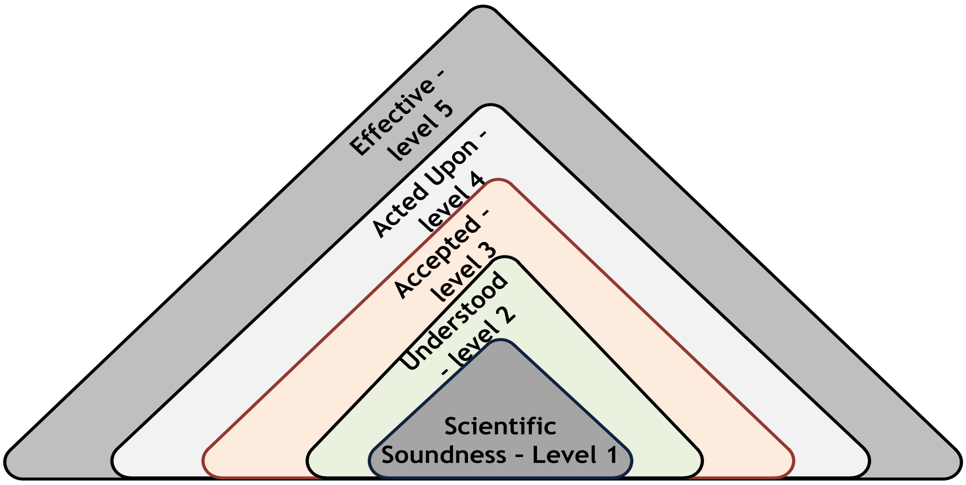

Figure 1-3: Defining the Research Scope (modified from Bots, 2003)

The research work presented in this thesis focuses primarily on the first three levels, meaning that it is scientifically sound, applicable as it is well understood by system analysts and hence accepted by required decision makers. The next two levels are susceptible to external influences which reduce the chances of being able to make validated and generalisable conclusions.

1.6 Contributions

The thesis building blocks are based on the fact that the only way to get ahead in the growing technological tumult will be to stay adaptable, especially at the conceptual design stage. To do that, we accept that the pace of change is not going to slacken – quite the reverse. Five contributions to theory and practice have emerged through the research of this thesis:

1. The proposed conceptual framework known as CXLUD: Complex Systems Lifecycle Understanding and Design offers an organised system design enabling environment which stimulates creativity and innovation for engineering organizations seeking to define value robust systems conceptual design.
2. Conceptualisation of three faces of complex adaptive systems conceptual model consisting of understanding, perception and action taken levels.
3. The identification and definition of CIRD conceptual model representing architectural challenges and issues facing complex adaptive systems architecting organisations.
4. A phenomenological study informed development of a managerial complexity competency model.

“Model” in this thesis means a description or analogy used to help visualise something that cannot be directly observed and “framework” is taken to mean a supporting or underlying structure. “Theory” is a belief, policy, or procedure proposed as the basis of an action.

1.7 Chapter Summary

This remainder of the thesis is structured as follows:

Chapter 2 provides an overview of topics in the literature that had significant influence over the synthesis of ideas in the research. The chapter also assesses the current state of the art in terms of complex adaptive system design methodologies.

Chapter 3 discusses those aspects related to research paradigm, methodology, epistemology, and design. This discussion involves justifying their appropriateness and showing their use throughout the research.

Chapter 4 presents results of an exploratory Delphi study identifying and organising complex adaptive systems architecting challenges and issues facing a complex adaptive system design and architecting organisation.

Chapter 5 develops the Complex Systems Lifecycle Understanding and Design (CXLUD) conceptual framework.

Chapter 6 introduces a case study to illustrate the CXLUD applicability to the context of architecting design principles establishment of Financial Systemic Risks Infrastructure Systems.

Chapter 7 provides an empirical validation of the CXLUD conceptual framework.

Chapter 8 presents results from a qualitative phenomenological study conducted to decipher how complexity theory can inform strategies for managerial complexity challenges. A competency model is proposed using the data collated from the phenomenological lived experiences study in the chapter.

Finally, Chapter 9 provides a summary of the research results together with the main conclusions. Some drawbacks of the research study are highlighted and recommendations for future research are discussed.

For ease of reference, the structure of this thesis is mapped to its aims and objectives and is summarised in Figure 1-4.

Thesis roadmap with information flow between the thesis structure

	CHAPTER AIMS	ACTIVITIES	OUTCOMES
1	INTRODUCTION		
	To provide an overview of the research and a guide to the thesis structure	Summarised the need for the investigation and decided upon the research focus, design and objectives	Scene setting, research aims and objectives
2	LITERATURE REVIEW & THEORETICAL FRAMEWORK		
	To explore the context of the research and	Reviewed relevant literature in & around the field, identified gaps in knowledge	Research gaps and contribution to theory (three faces of complex systems)
3	RESEARCH DESIGN		
	To consider relevant research approaches and to provide reasoning behind the chosen research design and data collection techniques	Systematically considered research design options. decisions regarding research approach and data collection techniques	Research Methodology
4	EXPLORATORY STUDY - Problem Management		
	To present the initial research findings and explore their relevance to the research question.	Industrial exploratory Delphi study on challenges in system architecting and issues	CIRD Model - a conceptual framework capable of organizing system architecting challenges and issues
5	IMPLEMENTING THE RESEARCH DESIGN		
	Presents a conceptual framework to support decision problems on design and control of complex systems.	architecting process and its individual steps. Methods and tools for bringing value robustness into conceptual design	Proposed conceptual Framework - CXLUD
6	CXLUD QUALITATIVE VALIDATION CASE STUDY		
	To demonstrate use of CXLUD in a real life architectural decision problem	Validate CXLUD principles using real-life case.	Satisficing process and procedure
7	CXLUD EMPIRICAL SUBSTANTIATION		
	To demonstrate the completeness of the constituents and definitions in CXLUD with group of practitioners	Explore project leaders perception on the goodness of the framework.	Satisficing process and procedure
8	QUALITATIVE PHENOMENOLOGICAL STUDY		
	To derived how insights from complexity science can informed strategy for coping with managerial complexity	Explore qualitatively the perceptions and lived experience of project leaders	Outcome is a phenomenological model (UPA), showing how complexity principles can inform managerial complexity
9	DISCUSSION & CONCLUSIONS		
	To illustrate how the findings have answered the research questions and provide the author's view on the research process and findings. To summarise the contribution to knowledge and to make recommendations for future research	Presentation and discussion of key findings. Also synthesis of key findings into contribution to knwoledge. Reflection of research findings and literature to highlight strengths and challenges and future research directions	• How the research findings address the research question • Researcher's reflection • Contribution to knowledge • Strengths and challenges • Future research

Figure 1-4: Research Outline, Activities and Outcomes

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CHAPTER 2 LITERATURE REVIEW

In the previous chapter, an overview of the thesis and the key contributions were presented. In this chapter, basic background and a literature review of various concepts needed for the understanding of the thesis are presented. Thus, the aim of this critical review of literature is to ground the research in current and relevant literature and subsequently identify gaps in existing knowledge and understanding. The review draws on several distinct bodies of literature that together reflect the inter-disciplinary nature of the thesis. The following literature review is structured in four sections.

In Section 2.1, we present how this thesis best fits within the body of complexity engineering research. In Section 2.2, selected previous systems design methodological approaches and design procedures are reviewed exposing areas of potential contribution to methodology. Selected key concepts critical for a common understanding in the thesis are reviewed in Section 2.3. Finally, a summary of the identified research gaps and opportunities are presented in Section 2.4.

The overview provided in this Chapter is by no means exhaustive. Figure 2-1 shows how this Chapter fits into the overall research process.

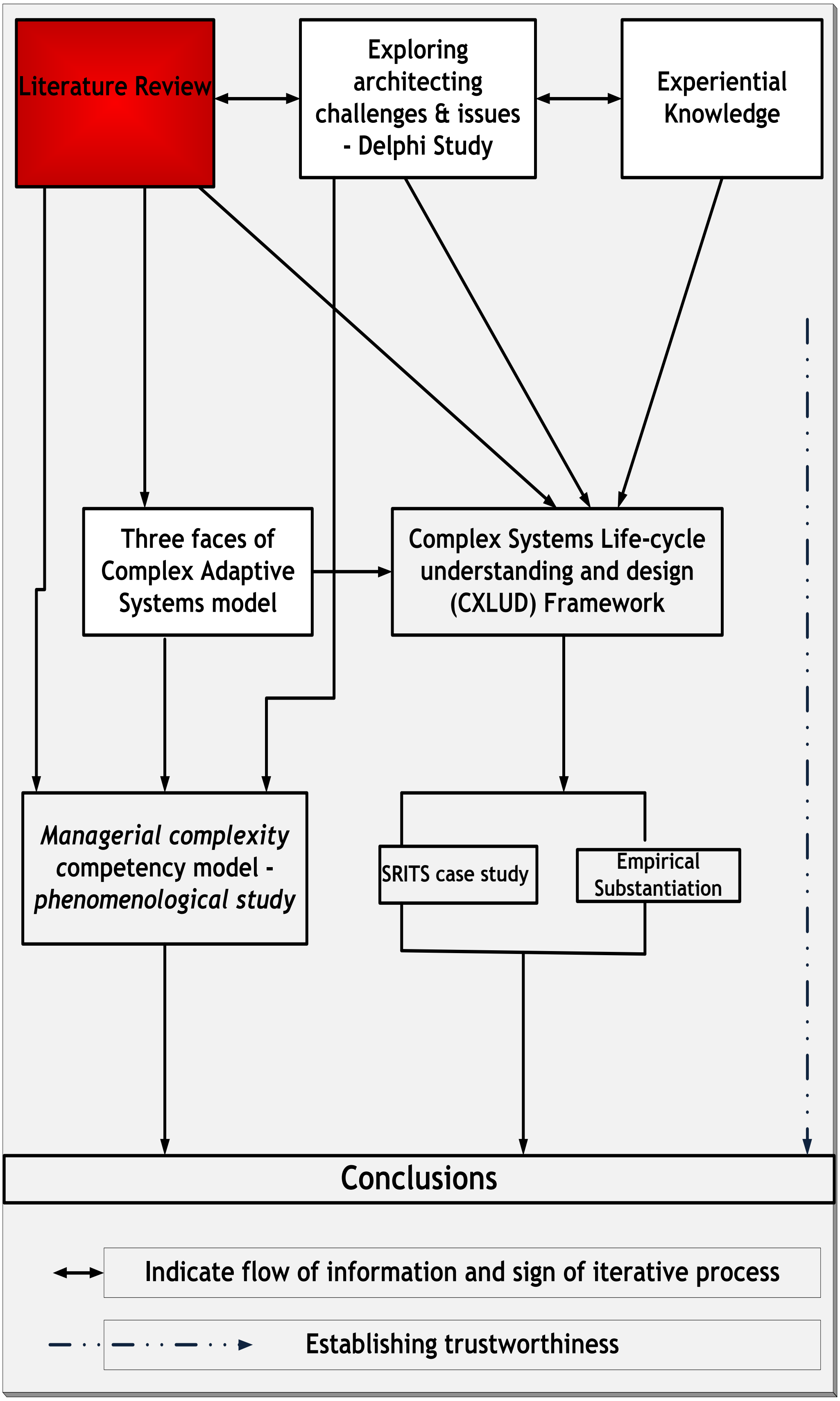


Figure 2-1: Research process with current stage highlighted

2.1 Complexity Engineering Design Research

This research can be subsumed under the term ‘complexity engineering’. Complexity engineering as a field of study is generally regarded as the application of complexity science knowledge to the system and engineering design research domain. Proposals have been made to harness complexity science for systems engineering design, yet insights from literature (e.g. Frei and Di Marzo Serugendo, 2012) indicate that the field is very dispersed and scattered over different existing disciplines. There are no methodologies, no common language and no common body of experience (Frei and Di Marzo Serugendo, 2012). Horvath (2004) summarises engineering design research in organisations. This summary shows the extent to which complexity engineering design research is a wide field capturing ideas and methodologies from engineering, complexity sciences and management. According to the Hovrath (2004), engineering design can be organised into *source, channel, and sink categories* of engineering design knowledge and research, respectively (Figure 2-2). The source categories are the categories that endow us with the fundamental mental capacity for engineering design. The channel categories provide knowledge for establishing a union between scientific/theoretical and pragmatic/technical knowledge of design. The union is achieved through different studies involving design philosophy, design theory, design methodology and design technology. Design theory research represents organisation of design knowledge to serve practical purposes and is concerned with general, specific, descriptive and prescriptive theories of design processes. Design methodology research represents design methods, activities and techniques providing guidelines for design. Design methodology research also includes design innovation (rationalising multi-disciplinary system development and creative concept generation) and modeling techniques (mathematical, symbolic, textual, verbal and visio-spatial approaches for representing design artifacts, knowledge and processes). The sink category is concerned with the (generation of) knowledge necessary for the ultimate deployment of the whole engineering design knowledge. For instance, design management is defined to support design activities and exploitation of particular design tools for particular products.

The studies carried out in this thesis best fit within a design theory and design methodology categories. The rationale here is that one aspect of the thesis includes development of design processes and design procedures with anticipation considerations in line with the definition of design methodology and design theory. Another aspect of the research presented in this thesis deals with acquiring phenomenological knowledge about decision making in managerial complexity and uses that data to propose a model which can assist management in planning the organization's future course of action. As such, this thesis is concerned with knowledge about design within the sink category.

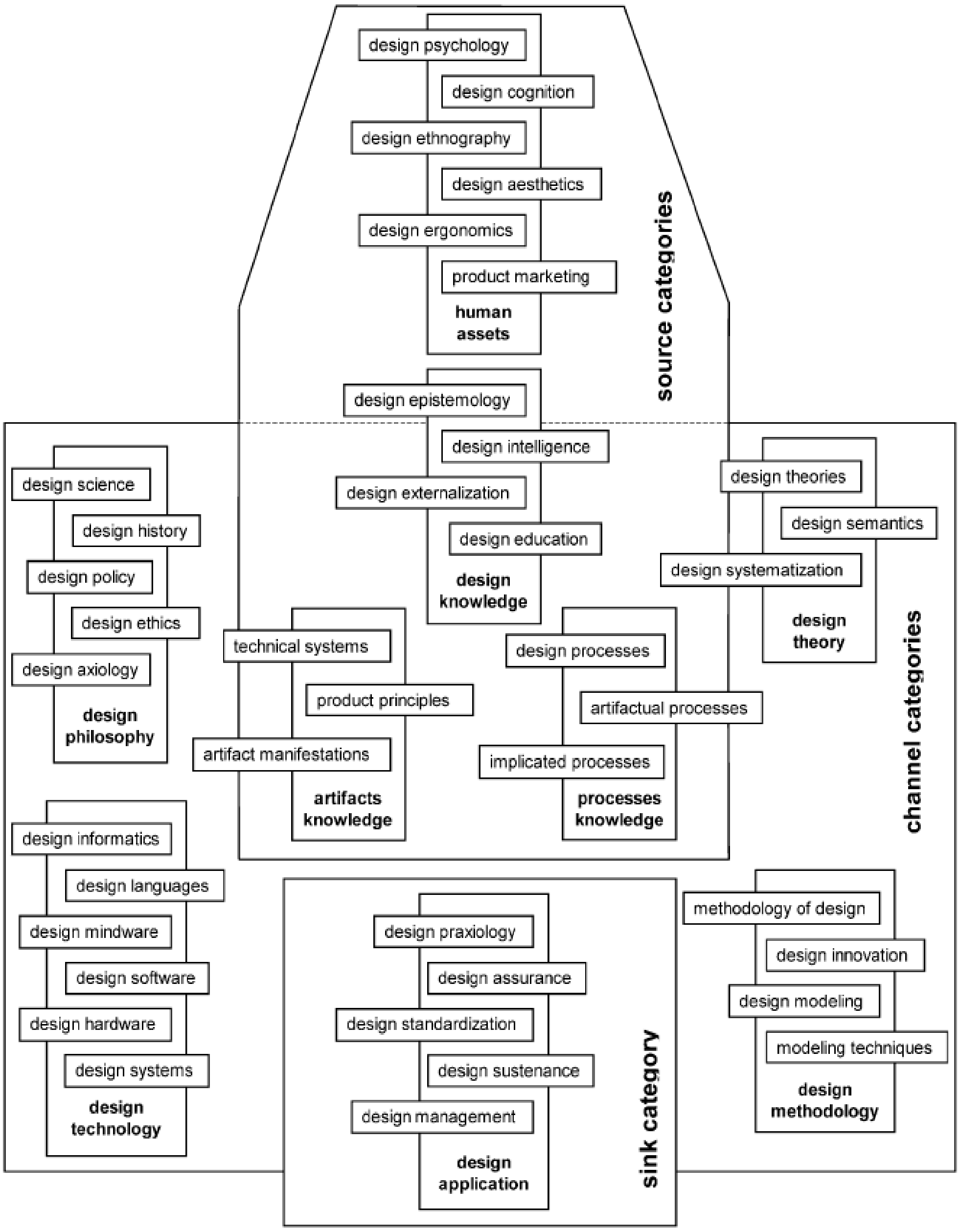


Figure 2-2: Framework of reasoning about categories, domains, and trajectories of engineering design research (Source: Horvath, 2004)

To further define what we take design methodology to mean in this thesis, we rely on the following definitions. Pahl and Beitz (1996) define design methodology as a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology and from practical experience in different domains. A design methodology must therefore:

- Encourage a problem-directed approach i.e., it must be applicable to every type of design activity regardless of the field of specialisation;
- Foster inventiveness and understanding i.e., facilitate the search for optimal solutions;
- Be compatible with concepts, methods and findings of other disciplines;
- Not rely on finding solutions by chance;
- Facilitate the application of known solutions to related tasks;
- Be compatible with electronic data processing;
- Be easily taught and learned and
- Reflect the findings of cognitive psychology and modern ergonomics i.e., reduce workload, save time, prevent human error and help to maintain active interest (Pahl and Beitz, 1996).

According to Blessing (1996), the purposes of design methodologies are to:

- Try to rationalise creative work;
- Reduce the probability of forgetting something important;
- Permit designs to be taught and transferred;
- Facilitate planning of the design process;
- Allow control of the process from the point of view of both efficiency and effectiveness and
- Improve communication between disciplines involved in design through a common set of concepts.

In complex adaptive systems design research, there are a number of well-known contemporary contributions in the field of design methodology and processes. In the next section, we present a review of selected methodologies and procedures.

2.2 Complex Adaptive Systems Design Methods and Procedures

This review examines the prescriptive models of the design process as prescribed in the design methodology literature. The purpose is to narrow down where the proposed method and procedure can contribute to engineering practice. This review is not exhaustive; nevertheless, it provides a comprehensive overview of the themes of interest to this thesis.

2.2.1 Gershenson's General Methodology

The general methodology by Gershenson (2007) provides guidelines for system development. It is composed of five iterative steps or phases: *representation, modelling, simulation, application* and *evaluation*.

The representation phase, according to given constraints and requirements is where the designer chooses an appropriate vocabulary, the abstraction levels, granularity, variables and interactions that have to be taken into account during system development. The system is divided into elements by identifying semi-independent modules, with internal goals, dynamics and interactions with the environment. The representation of the system should consider different levels of abstraction.

In the modeling phase, a control mechanism is defined which should be internal and distributed to ensure the proper interaction between the elements of the system and produce the desired performance. However, the mechanism cannot have strict control over a self-organising system; it can only steer it. To develop such a control mechanism, the designer should find aspects or constraints which will prevent the negative interferences between elements (reduce friction) and promote positive interferences (promote synergy). The control mechanism needs to be adaptive, be able to cope with changes within and outside the system (i.e., be robust) and be active in the search for solutions.

In the simulation phase, the developed model(s) are implemented and different scenarios and mediator strategies tested. Simulation development proceeds in stages: from abstract to particular. The models are progressively simulated; based on the results, the models are refined and simulated again.

The application phase is used to develop and test model(s) in a real system. Finally, in the evaluation phase, the performance of the new system is measured and compared with the performances of previous ones.

Key limitations of the Gershenson's General Methodology are that the various stages of the process assume that managers and designers know what needs to be done and that this information can be included in a specification. The specific issue of the right creative environment that gives a better guarantee of rapid improvement and innovation than planning is not well addressed.

2.2.2 OPM Methodology

Object Process Methodology (OPM), developed by Dori (2002) is a methodology used in product design and engineering. In OPM, a system is defined as an object that exhibits function, where the function is “the main intent for which was built, the purpose for which it exists, the goal it serves” (Dori, 2002: pp 251). Under OPM, both the object and function can be decomposed hierarchically in a well-defined manner into several hierarchical levels, integrating relationships between objects, functions, operators and operands.

OPM has major limitations. First, it does not recognize, mention or include any consideration of the broader socio-environmental context in which the system is built and operates. Because it fails to do this, OPM’s representation of the system is biased against any contextual influence on its behaviour or form. OPM’s social domain considerations do not go beyond possible interaction of a system with its operators and customers. There is also no explicit consideration of the temporal system properties or ilities.

2.2.3 CLIOS-OPM Integrated Method (COIM)

Complex, Large, Interconnected, Open, Socio-Technical Systems (CLIOS) and OPM Integrated Method (COIM) developed by (Osorio et al., 2011) is for analysing the architecture of a complex socio-technical system and the evolution of such architectures. Their work combines the OPM for studying a system’s architecture in terms of its structure and behaviour with the CLIOS. COIM recognises the utility of architecture frameworks for analysing the form and function of a socio-technical system and the associated outside influences on that system. An obvious focus of COIM approach to understanding the architectural evolution of a socio-technical system is backward-looking with an objective of understanding the system’s history and sources of influence in the system’s development.

This thesis has an opposite focus to COIM. Working at the systems conceptual design level, the method proposed in this thesis will be forward-looking with the objective of supporting efforts to guide a system’s design and evolution.

2.2.4 Multi-Attribute Tradespace Exploration (MATE)

The MATE process incorporates decision theory into a model and simulation-based design.

MATE is a technique for quantitatively exploring large design tradespaces populated by architectural candidates produced by various model-based methodologies. At a high level, MATE has five phases: Needs identification, Architecture Solution Exploration, Architecture Evaluation, Design Solution Exploration, and Design Evaluation (Ross, 2006).

According to Ross et al., (2004), the MATE framework provides a structure for developing technical, political, market, and budgetary uncertainty analysis of a proposed system. It also allows for the consideration of several beneficial design theories during the conceptual phase, that is, design for manufacturability and assembly, deployment, operations, maintenance and retirement through the inclusion of key downstream stakeholders.

While MATE allows all possible design concepts to be evaluated and compared on a single tradespace, it represents a static view of the system based on a given stakeholder's perception of the existing operating concept, environment, context and needs at that point in time. Also, because outer environment exogenous changes will happen over time, it is critical to devise an approach that helps systems architects and engineers anticipate creatively possible dynamic changes. Theoretically, using MATE, large teams of dedicated, well –coordinated tradespace model builders and integrators could handle most needs within a severely limited time frame, but such resources are rarely allocated so early in the process.

The time to perform an analysis depends on the availability and skills of the supporting designers and architects, as well as the particular nature of the problem. Unfortunately, the time and cost necessary to assemble a suite of integrated, customised models can often exceed the resources available to a great number of projects in the early systems conceptual design phase and are, in most cases, beyond the capability of small enterprises.

Thus in practice, despite the theoretical and demonstrated usefulness of MATE, project leaders faces immense pressure to select a single baseline without rigorously establishing the desirability of their choice within a suitable context. The approach proposed in this thesis will addresses this problem by offering a low-cost approach for rapidly creating and analysing a complex adaptive system's design tradespace.

2.3 Key Concepts and Sources of Theory

It is important to note that definitions are necessary in the process of the research study but the definitions *per se* are not the goal of this research. Some core concepts, including

Uncertainty, Value Robustness, System Architecture, Complexity and Complex Adaptive System are presented in some detail, as these concepts are critical for common understanding in the thesis. Additional terms have been defined as and when they are used throughout this thesis. Further definitions of terms and concepts used are provided in Appendix A.

2.3.1 Coping with the unknown - uncertainty

A major characteristic of complex adaptive systems is the uncertainty which comes in part from the large number of potential interactions which can exist within the system and between the system and its reference environment. A framework to aid in the understanding of uncertainties and techniques for mitigating and even taking positive advantage of them is presented by McManus and Hastings (McManus and Hastings, 2006). They introduce a framework which relates the problem of uncertainty to the desired outcome of ilities. In Figure 2-3, the proposed framework for handling uncertainties and their effects is broken into four categories: uncertainty, risk/opportunities, mitigations/exploitations and outcomes.

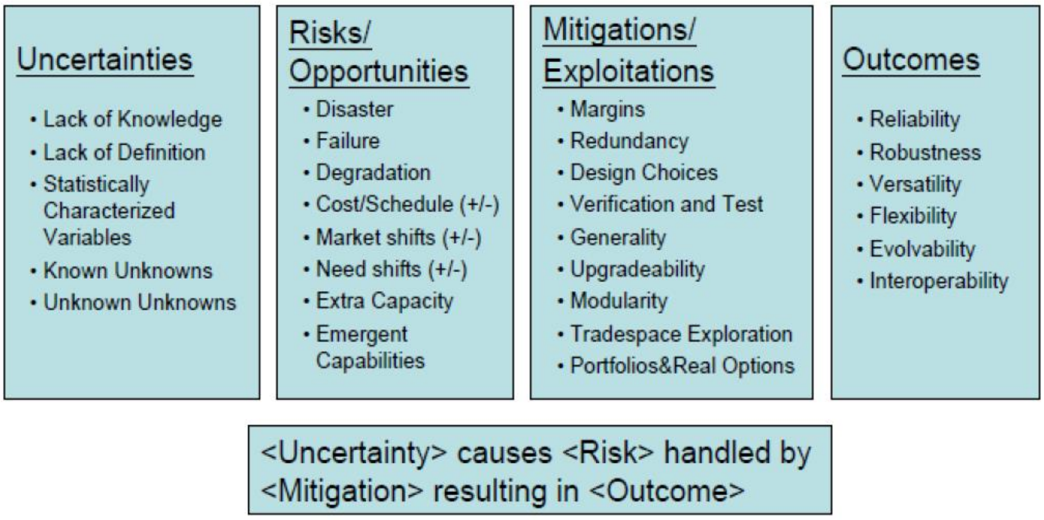


Figure 2-3: Framework for Handling Uncertainty (McManus and Hastings, 2006)

This framework (Figure 2-3) shows how there are many possible pathways in dealing with the numerous types of uncertainty. Uncertainties in the world lead to consequences in the form of risk or opportunities. These consequences can be either mitigated or exploited through certain decisions or actions such as introducing margin, redundancy, verification and testing, modularity, open architecture, standardization or decision analysis tools. Those decisions relate to attributes of the system that characterize the interaction with uncertainty, like reliability, robustness, versatility or evolvability (McManus and Hastings, 2006).

Hastings and McManus have described outcomes as a desired attribute of the system that is the result of a mitigating or exploiting strategy. It would seem that some of these six, such as robustness, versatility, flexibility, and evolvability could also be considered system strategies that are useful in creating specific system outcomes. In addition, decision making is an all-pervading activity in complex adaptive systems designs and management.

While many strategies exist as a means of coping with uncertainty, this research will primarily focus on the strategy of evolvability. Other additional strategies for dealing with uncertainty that can be deployed in complex adaptive systems are discussed in the next section.

2.3.2 System Properties: Ilities

It is generally known that successful complex adaptive systems will use combinations of temporary system properties or 'ilities' to maintain their integrity in a changing and unexpected environment. De Weck et al., (2012) describe system properties i.e., the "ilities," as reflecting the degree to which systems are able to maintain or improve function in the presence of change and emphasise that the "ilities" constitute a rich research area for improving value delivery over the system lifecycle. Ilities are system properties increasingly recognized as qualities that lead to successful systems (McManus et al., 2007).

The definitions of these selected ilities are presented in Table 2-1.

Table 2-1: Selected ilities with definitions

Ility Name	Definition ("ability of a system…")
value robustness	Ability of a system to maintain value delivery in spite of changes in needs or context (Source: de Weck et al., 2012)
	Ability of an entity to maintain value delivery in spite of shifts in contexts, needs, or design (Source: Beesemyer, 2012)
adaptability	Ability of a system to be changed by a system-internal change agent with intent (Source: de Weck et al., 2012)
	Ability of an entity to be changed by a system-external change agent (Source: Beesemyer, 2012)
agility	Ability of a system to change in a timely fashion (Source: de Weck et al., 2012)
	Ability of an entity to change in a shorter time span with respect to a threshold value (Source: Beesemyer, 2012)

changeability	Ability of a system to alter its operations or form and consequently possibly its function, at an acceptable level of resources (Source: de Weck et al., 2012)
	Ability of an entity to alter form, function or ops (Source: Beesemyer, 2012)
evolvability	Designed to be inherited and changed across generations (over time) (Source: de Weck et al., 2012)
	Ability of an architecture to be changed between generations in response to general shifts in context or needs (Source: Beesemyer, 2012)
extensibility	Ability of a system to accommodate new features after design (Source: de Weck et al., 2012)
	Ability of an entity to increase a parameter set during ops by internal or external change agents (Source: Beesemyer, 2012)
interoperability	Ability of a system to effectively interact with other systems (Source: de Weck et al., 2012)
modularity	Degree to which a system is composed of modules (not an ability-type ility) (Source: de Weck et al., 2012)
reconfigurability	Ability of a system to change its component arrangement and links reversibly (Source: de Weck et al., 2012)
robustness	Ability of a system to maintain its level and/or set of specified parameters in the context of changing system external and internal forces (Source: de Weck et al., 2012)
	Ability of an entity to maintain a specified parameter during operations in spite of shifts in context, or needs (Source: Beesemyer, 2012)
scalability	Ability of a system to change the current level of a specified system parameter (Source: de Weck et al., 2012)
	Ability of an entity to change the level of a parameter (Source: Beesemyer, 2012)
survivability	Ability of a system to minimize the impact of a finite duration disturbance on value delivery (Source: de Weck et al., 2012)
	Ability of an entity to maintain a specified parameter during operations in spite of disturbances in context, needs or design (Source: Beesemyer, 2012)
versatility	To satisfy diverse needs for the system without having to change form (Source: de Weck et al., 2012)
	Ability of an entity to change its set of functions or operations while maintaining original form during operations (Source: Beesemyer, 2012)

Flexibility	Ability of an entity to be changed by a system-external change agent (Source: Beesemyer, 2012)

If these ilities are desirable outcomes that need to be verified and validated in future systems, there needs to be a discussion on what these words mean. Having an ility hierarchy could prove useful in designing systems for the specific desirable qualities that may be required. Insights from the literature indicate that constructing such a hierarchy is a difficult task.

An exploratory study in this endeavour is outlined in (de Weck et al., 2012); relationships amongst ilities to better understand which may support (means) other ilities (ends) that lead to ultimate value delivery over the lifecycle of systems were investigated. De Weck suggests that value robustness can be considered as the root node, that is, the ultimate goal of engineering systems design (i.e., what the authors called level 0). This notional relationship is represented in Figure 2-4.

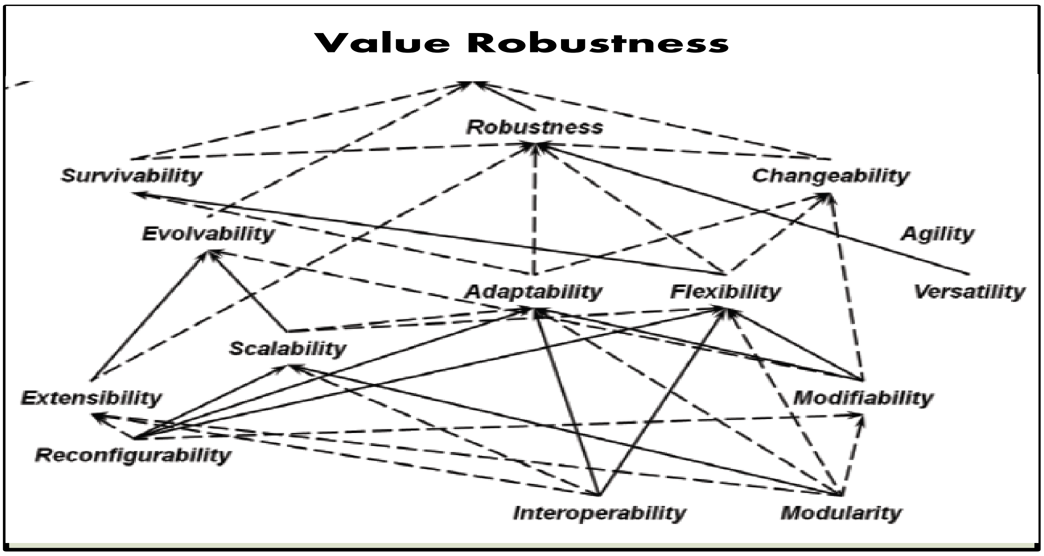


Figure 2-4: Value robustness and ilities(Source: de Weck et al., 2012)

As illustrated in Figure 2-4, the ilities that directly enable value robustness are (from left to right): survivability, evolvability, robustness and changeability, with robustness deemed to be the closest ility to value robustness. Each of these ilities is in turn enabled by other ilities, for example robustness is enabled by versatility and evolvability is enabled by extensibility, scalability and modifiability. The "bottom" ilities enable many other ilities, for example interoperability enables extensibility, scalability, adaptability and flexibility, while modularity and reconfigurability each enable the same four ilities plus modifiability.

According to Cotton et al., (2009), to develop an initial set of “ility” values a number of questions are usually considered by the different authors based on personal experience and literature review such as: What are the overall objectives? What values are essential to ensuring effective joint force protection? What values are essential to architectures? Using iterative introspection with experience and literature, more than 120 ilities were considered and filtered in an attempt to answer these questions. Figure 2-5 shows the resulting sets of hierarchies in “architecture quality” and “system effectiveness.”

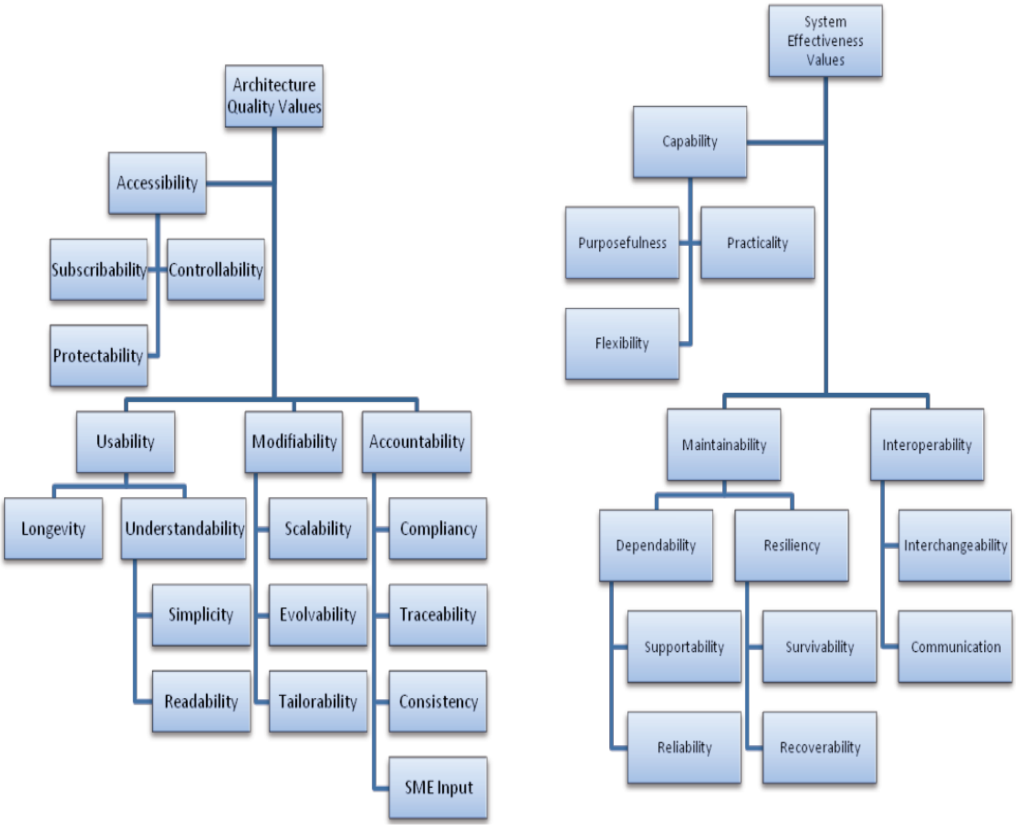
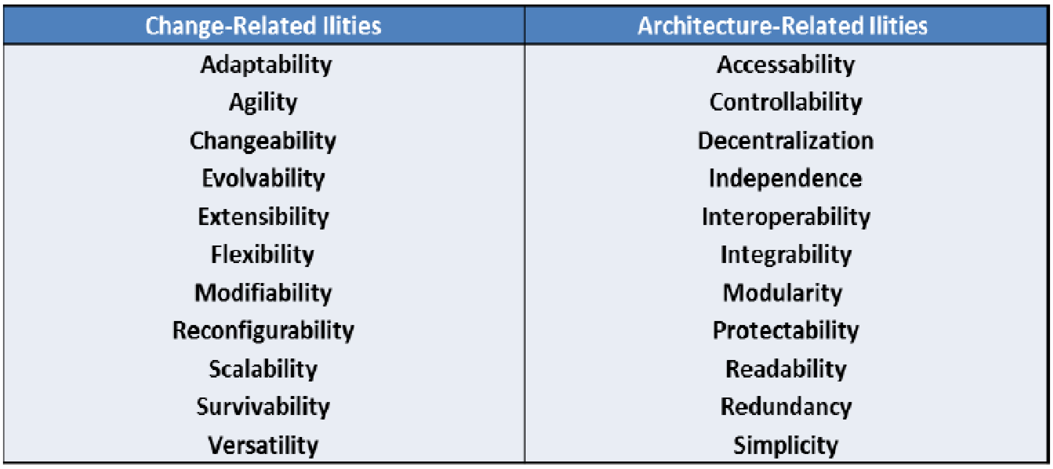


Figure 2-5: Ilities Hierarchies for "Architecture Quality" (left) and "System Effectiveness" (right) (Cotton et al., 2009)

Relying on the definitions of previous authors, Beesemyer (2012) conducted research synthesizing different ways to look at ilities as sets. Figure 2-6 shows the outcome of the Beesemyer (2012) classification that fit ilities into change-related and architecture-related semantic fields.



Change-Related Ilities	Architecture-Related Ilities
Adaptability	Accessability
Agility	Controllability
Changeability	Decentralization
Evolvability	Independence
Extensibility	Interoperability
Flexibility	Integrability
Modifiability	Modularity
Reconfigurability	Protectability
Scalability	Readability
Survivability	Redundancy
Versatility	Simplicity

Figure 2-6: Change-Related and Architecture-Related Ility Examples (Source: Beesemyer, 2012)

Detailed definitions of these ilities are available in the quoted references and will not be repeated further here; however for a few of the ilities there will be more discussion in the next sections.

2.3.2.1 Value robustness

Value robustness is the ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs (Ross and Rhodes, 2008a). There are many ways systems can achieve that goal - actively changing to meet new needs or passively remaining robust. The important aspect to be noted is that value-robustness only demands continued delivery of value. Thus, value robustness is taken in this thesis to be a strategy that may use various other ilities in its attempt to maintain system value delivery over time, in spite of context changes. Value-robustness is an ility that applies at the overall system value level and it is taken as the ultimate goal of most systems engineers in the presence of changing conditions. It is the motivating principle to changing the way we architect systems and therefore encompasses many of the strategies in literature of achieving that aim, including passive and active means.

2.3.2.2 Evolvability

Evolvability has significantly less literature in complex adaptive systems engineering than other ilities defined above. Evolvability generally is associated with biological references. Kirschner and Gerhart (1998) define evolvability as an organism’s capacity to generate heritable phenotypic variation. Beesemyer et al., (2011) define evolvability as the ability to change an inherited design across generations [over time]. From a system architecture perspective, Beesemyer (2012) define evolvability as the ability of an architecture to be inherited and changed across generations [over time]. McManus and Hastings (2006) describe evolvability as the ability of the system to serve as the basis of new systems (or at least generations of the current system) to meet new needs and/or attain new capability levels. In systems architecture literature, Butterfield et al., (2008) defines architecture evolvability as the ability of the architecture to handle future upgrades. This research goes on to say that evolutionary systems require "a process to plan, define and prepare for program spirals" by identifying key technologies, processes and attributes that will be required to support future capabilities. Other researchers have attempted to suggest heuristics to assist system architects to devise evolvability strategies. According to Whitacre and Bender (2009), degeneracy is unique in its ability for providing high levels of robustness while also allowing for future evolvability.

2.3.2.3 Changeability

Fricke and Schulz (2005) characterize changeability as the ability of a system to change easily. Changeability encompasses the active strategies of value robustness. The motivation for changeability in a system is categorised into three major drivers according to Fricke and Schulz (2005): 1) dynamic marketplace, 2) technological evolution and 3) variety of environments. These drivers require that systems architectures address: 1) the ability to be changed easily and rapidly and 2) insensitivity or adaptability towards changing environments (Schulz et al., 2000).

Changeability is often mentioned with other ilities in the literature (flexibility, adaptability, scalability and modifiability). Fricke and Schulz (2005) decompose changeability into four categories: robustness, agility, adaptability and flexibility (Figure 2-7). Changeability is a high-level ility that contains the various ways a system can change states.

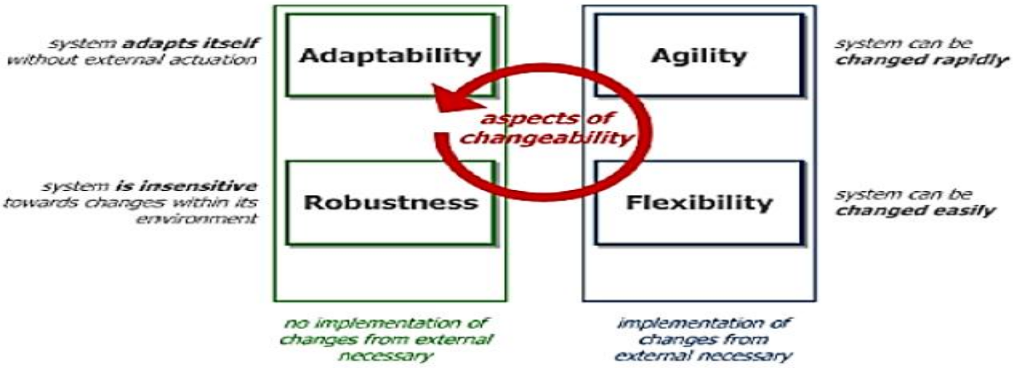


Figure 2-7: Changeability as Four Ilities (Fricke and Schulz, 2005)

A more acceptable construct for defining changeability in systems engineering is given in Ross (2006). Ross (2006) defines a change made to a system as a transition from one state to an altered state over time. Every change can be characterised by three elements (Figure 2-8):

1. The change agent
2. The change mechanism
3. The change effect

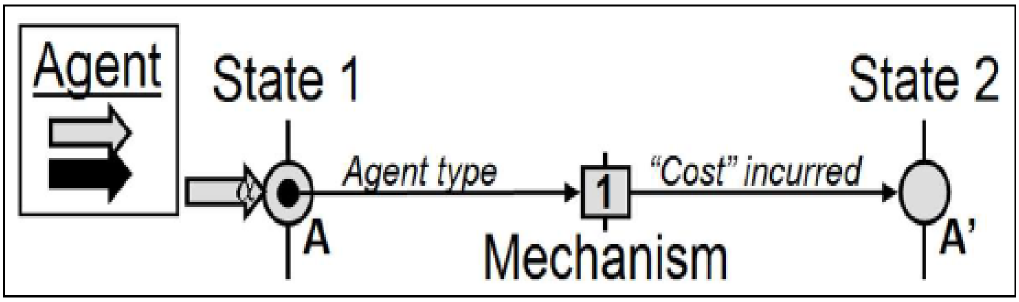


Figure 2-8: System Change Framework (Ross et al., 2008)

The change in Figure 2-8 is a simplified case of a system change with only one particular change being captured. A change in this framework is represented by a path from State 1 to State 2. Changeability then is the ease with which a system can undergo various changes.

2.3.3 System Architecture and System Architecting

A feature that is common to many systems is architecture. The literature is littered with numerous efforts for defining or describing what systems architecting is, or is not. Many aspects of "architecture" may be fixed, with some aspects being varied. From a review of current literature, it becomes clear that there has been an increasing effort towards the study and design of systems architecture. For the research objectives defined in this thesis, what system architecting and system architectures are must be well understood to internalise the constructs being presented. To do that, we consider the following definitions of architecture:

Mekdeci et al., (2011) define an architecture as consisting of two core elements: 1) what the system is composed of, known as the operational elements and components (i.e., the form), and 2) how the system operates, known as the Concept of Operations (CONOPS) (i.e., the operations). Rozanski and Woods (2005) define system architecture to have four different aspects:

- Its static structure tells us how elements of a system have been designed and how they are arranged.
- Its dynamic structure, describes how elements will work when the system is running.
- Its externally visible behaviour defines how external users and other applications in the computational environment interact with the system.
- Its quality properties, which are non-functional characteristics of the system, serve to qualify how it operates, interacts and gives results.

According to Osorio et al., (2011) a system's architecture is the embodiment of a concept for achieving the desired system's function in terms of its form, i.e., its structure-behaviour combination**.** A system's architecture can be affected by various factors not only during its design, construction and first implementation, but also throughout its entire operational lifetime *via* changes in its form (structure, behavior or both), function or concept (Crawley and Weigel, 2004). Architecture includes a set of allowable designs. The activity of creating architecture is usually called 'architecting'. According to Dauby et al., (2010) system architecting is simply a search process whose goal is to efficiently navigate a near infinite combination space in pursuit of a solution that is best able to satisfy a multitude of competing system goals. As illustrated in Figure 2-9 adapted from Muller (2012), the process of creating a new product is called the Product Creation Process (PCP). A multi-disciplinary team, the PCP team, creates the product. The input to the PCP comes from all stakeholders, with their needs, concerns, expectations etc. The architect is responsible for the quality of the architecture: a system that meets the stakeholder's expectations provides the stakeholders with an attractive and useful experience and that can be realized by the PCP team. The architecting activity transforms problem and solution "know how" into a new architecture.

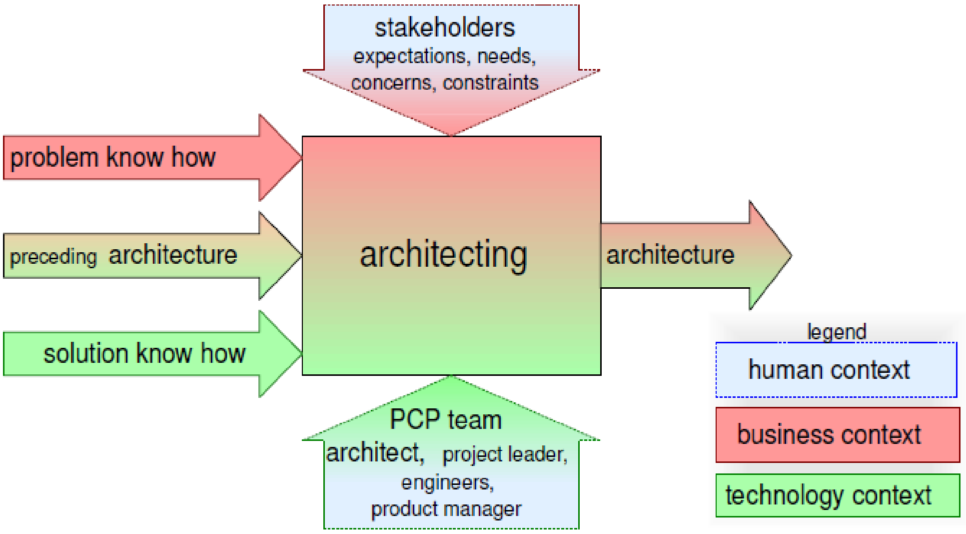


Figure 2-9: Architecting = creating architecture definition (Source: Muller, 2012)

The IEEE Std. 1471 (IEEE, 2000) defines architecture as the fundamental organisation of a system embodied in its components, their relationships to each other and to the environment and the principles guiding its design and evolution.

2.3.4 Complexity Theory Explored

One of the most common problems when discussing complex adaptive systems is the meaning of 'complexity'. Complexity is not a well-defined subject and opinions about what the field constitutes differ from person to person (Mitchell, 2009). Surveys of the literature distinguish between classes of definitions of complexity (Mitchell, 2009). The goal of the overview provided in this section is to introduce the reader to some of the vocabulary employed in the literature. It is not the intention to develop or distill a coherent theory of complexity; such a task would be well beyond the scope of this thesis. In referring to complexity theory, this thesis refers to the whole field of complexity theories and does not point at one particular theory. Also, it is important to stress that there exist many different sets of concepts in these complexity theories. The concepts introduced here do by no means form a complete account, nor should the exclusion of certain concepts be regarded as a rejection of their validity. Nevertheless, the concepts introduced in this chapter are central to the field of complexity and should provide the reader with an adequate feel of what the field constitutes. Complexity arises from interactions between diverse actors with inter-dependent behaviours who adapt to one another (Miller and Page, 2008). To ground our discussions firmly in theory, we start by discussing descriptions given by (Page, 2010) and Simon (1996).

In (Page, 2010), the author suggests that many definitions fall into the following two broad categories.

- BOAR. Complexity lies between order and randomness.
- DEEP. Complexity cannot be easily described, evolved, engineered or predicted.

BOAR places complexity between ordered and randomness. Ordered systems are not DEEP. They can be described, engineered and predicted. Often, they can be evolved as well. Random processes are also easily described and engineered and, if stationary, easily predicted (at least at the distribution level). In contrast, a complex process cannot be described in just a few words, nor be predicted accurately. Thus, what lies between order and randomness will tend to be DEEP. Simon (1996) refers to complexity as something that is “made up of a large number of parts that interact in a non-simple way” (Simon, 1996,pp. 195). According to Simon (1996), complexity is hierarchical in nature and each system within the hierarchy has its own unique set of sub-systems. He describes this as a “box within a box,” with each complex system consisting of both an inner and outer environment (Simon, 1996, pp. 148). The outer environment serves as the operating environment for the inner environment and the outer environment is the inner environment’s primary source of complexity. For its part, the inner environment is constantly adapting and insulating itself from the variations emerging from the outer environment; this is referred to as a “design problem” (Simon, 1996, pp. 134). The inner environment’s design quality also depends on the limited data available from the outer environment and this leads to a high level of uncertainty and ambiguity. Thus, a central aspect of complexity theory is that it regards systems as open or dissipative. The idea of dissipation thus relates to the fact that complex systems interact with their environment in order to maintain their stability. Complexity theory thus consists of a set of theories that try to conceptualize and represent the workings of complex systems.

This outlines why there is a design problem. The result of the complexity existing in the system creates a need for a method and competencies that can handle this set of interconnecting technical, organizational and process considerations.

2.3.5 Complex Adaptive Systems

The study of complex adaptive systems is an inter-disciplinary field (Mitchell, 2009). To understand the components of complex adaptive systems, we first separate and describe individually the three words: “complex”, “adaptive” and “systems”. All three terms in the name Complex Adaptive Systems are significant in the definition of what a Complex Adaptive Systems is.

“Complex” means composed of many parts which are joined together. Complex implies diversity, many connections among a wide variety of elements. According to Weng et al., (1999), in a general sense the adjective "complex" describes a system or component that by design or function or both is difficult to understand and verify. “Adaptive” refers to the fact that all living systems dynamically adapt to their constantly changing environments as they strive to survive and thrive. That is, adaptive suggests the capacity to alter or change and also the ability to learn from experience. The word “system*”* is used in many different ways in many contexts; the sense intended here is that of an engineered creation. The International Council on Systems Engineering (INCOSE) defines a system as a combination of interacting elements organized to achieve one or more stated purposes and an integrated set of elements, subsystems or assemblies that accomplish a defined objective. These elements include products (hardware, software, and firmware), processes, people, information, techniques, facilities, services and other support elements (INCOSE, 2007).

While it is difficult to exactly define complex adaptive systems, Rouse and Serban (2011) note that: complex adaptive systems are a special type of complex systems which are composed of independent (or conditionally independent) agents whose behaviour can be described as based on physical, psychological or social rules, rather than being completely dictated by the dynamics of the system. Overall, system structure and behaviour inherently changes over time. The behaviours of complex adaptive systems can usually be influenced more than they can be controlled (Rouse and Serban, 2011).

According to (Brownlee, 2007), complex adaptive systems refer to a field of study and resultant conceptual framework for natural and artificial systems that defy reductionist (top-down) investigation. Such systems are defined as being composed of populations of adaptive agents whose interactions result in complex non-linear dynamics and emergent system phenomena (Brownlee, 2007).

More precise definitions and examples for the systems engineering community are provided by Sheard and Mostashari (2009), Sheard (2005), Minai et al., (2010) and Maier and Fadel (2010).

2.3.6 Project Complexity and Competency Model

Although the need for qualitative project complexity management research has been identified (Cicmil et al., 2009), insights from literature indicate a lack of a clear definition of project complexity. The result causes confusion amongst project management academics and practitioners regarding what makes a project complex to manage. A recent paper by Maylor et al., (2008), is a step towards changing this situation. Maylor et al., (2008) present a qualitative empirical model which captures both structural and dynamic elements of managerial complexity in projects. The model is called MODeST. They distinguish the dimensions of “Mission”, “Organization”, “Delivery”, “Stakeholders” and “Team” under which several concepts were defined per dimension, in total resulting in more than 100 underlying concepts. Managerial complexity varies with (and is defined by) a particular project’s context – for instance, a project may have several stakeholders with conflicting requirements, whereas another may have only one stakeholder. The MODeST model describes managerial complexity using the five dimensions and several sub-dimensions. A key limitation of the MODeST model is a lack of exploration of the possibility of managing complexity and competencies necessary for successful management. This provides an opportunity for further research.

Thomas and Mengel (2008) make the link between complexity in project management and competency. They assert that as organisations become more complex, it is necessary to have an understanding as to what is meant by complexity and point out the numerous inter-relationships to consider, all of which make it necessary for practitioners to make decisions based on variables that are not known. Their research emphasises that project managers may not be able to handle complex projects and discusses the need for “master project managers” to have competencies in areas including shared leadership, social competence and emotional intelligence, communications, organisational political skills and vision, values and beliefs.

2.3.7 System Design and Value Focused Thinking (VFT)

The literature review reveals a wide diversity of opinions and many speculative assertions on the real meaning of value. In spite of the centrality of the value concept in system design, there is still relatively little knowledge about what value is, what its characteristics are and how system designers determine it. The approach taken in this thesis to the modeling of value is within a system engineering framework and complexity theories. Systems engineering is a rich combination of the mathematical theory of systems, behavioral theory supported by new technologies in a setting that facilitates the resolution of real world complex problems (Sage and Rouse, 1999).

According to (Carlson and Doyle, 2002), two great abstractions govern the study of complex (adaptive) systems:

1. Separate systems engineering into control, communications and computing and emphasize the development of theory and applications.
2. Separate systems from physical substrate.

The system engineering methodology is a framework that consists of seven stages (Sage and Rouse, 1999).Here these stages are described in light of modeling the interdependent complex adaptive systems.

- *Problem definition.* In modeling the behaviour of complex adaptive systems one distinguishes between modeling one system at a time and capturing the interdependencies.
- *Value system design* includes 1) the definition of objectives and their ordering in a hierarchical structure ; 2) determining the relations between objectives and practical constraints ; and 3) the definition of the metrics that determine the attainment of the objectives.
- *System synthesis* follows the value system design. This stage is responsible for collecting alternative approaches pertaining to each objective and the description of these approaches.
- *System analysis and modeling.* The analysis of complex adaptive systems comprises two parts : one is a detailed behaviour, described by the subject matter experts and the other one is the attempt to capture the perceptions of the underlying theories and abstractions that are both accurate and subject to computer simulations.
- *Optimization of alternatives and their ranking* is a collection of iterations of the previous steps. This stage aims to reduce the number of alternatives - and courses of action - through the application of a variety of analysis procedures that are highly contextual.

- *Decision making.* Metrics for determining the attainment of objectives are defined during the synthesis phase. Activities and metrics for guiding subsequent activities toward the development of a complete program plan are defined during the decision making stage.
- *Planning courses of action (analysis of alternatives)* is the implementations of the tasks and objectives determined in the previous steps. This stage involves decision makers and subject matter experts at all levels where the attainment of objectives is relevant.

The above definition of value in system design is parallel to the characterization of value by Keeney (1992). According to Keeney (1992), value is what decision maker cares about in decision-making and is typically measured with utility function, value function or preference function. They range from ethical principles that must be upheld to guidelines for preferences among choices.

VFT essentially consists of two activities: first deciding what you want and then figuring out how to get it. To think of these values in a decision process, the decision must have the following properties: the decision should be a real problem, it should be of great importance and it should be complex and have no absolute solution. The decision maker should be able to answer the "why is this important" test. If the decision has no real importance the input to the decision will not carry the necessary relevance to make a true decision. Keeney (1992) lists some of the benefits as guiding information collection; evaluating alternatives; interconnecting decisions; improving communications; facilitating involvement in multiple-stakeholder decisions and guiding strategic thinking.

2.3.8 System Design Theory

People have long recognised that evolvability, achieved most fundamentally by appropriate modularity in design, can have enormous technical, organisational and ultimately economic value. People have been analyzing design evolvability and changeability in qualitative, intuitive, and heuristic ways; for example, the Baldwin and Clark's (2000) theory of design evolution. The crux of the theory is that modularity in design - an observable property of designs and design processes - dramatically alters the mechanisms by which designs can change. A modular design in effect creates a new set of modular operators, which open up new pathways of development for the design (Baldwin and Clark, 2000).

The parts of Baldwin and Clark's theory that are most relevant to this thesis are the evolution of modular design as adaptive systems under the action of modular operator. Baldwin and Clark (2000) define six modular operators, which form a basic repertory of actions that can be applied to any modular design. They are:

1. Splitting a system into two or more modules.
2. Substituting one module design for another.
3. Augmenting - adding a new module to a system.
4. Excluding a module from the system.
5. Inverting to create new design rules.
6. Porting a module to another system.

Baldwin and Clark (2000) economics of design which itself builds on Holland's (1992) theory of complex adaptive systems, view designs as structures that evolve through the purposeful actions of designers. In contrast to biological evolution, which is fueled by random variation among members of a population, the raw material for design evolution is supplied by designers that "see and seek value in new designs" (Baldwin and Clark, 2000, p. 35). Baldwin and Clark emphasise that value-seeking designers need to consider not only the structure of an existing design but the space of possible designs and the actions needed to realise them. While the concept of evolution by natural selection had its origin in biology, the study of evolutionary dynamics in human designs relies most directly on ideas from the inter-disciplinary field of complex systems.

The choice of a component standard typically precedes choices about component design. The decision process is thus bounded by human rationality (Simon, 1977). According to Rubinstein (1998), in order to model decisions under bounded rationality, it is indispensable to explicitly specify decision-making procedures. A seminal decision procedure was made by Herbert Simon, who proposed a 3-stage stepwise process in principle (1977). The three steps are intermingled. The three steps are:

1. Framing (intelligence) – finding occasions for making a decision.
2. Design – finding possible courses of action.
3. Choice – choosing among courses of action.

The concept of 'CXLUD framework' (Chapter 5) and 'three faces of a complex adaptive system' (Chapter 4) developed in this thesis were rooted in Baldwin and Clark's (2000) theory of design evolution and Simon's (1977) model of the decision making process.

2.4 Research Opportunities and Gaps

This section identifies the research gaps to be addressed by this thesis. In Section 2.4.1, we highlight a research gap related to complex adaptive systems architecting. Section 2.4.2 will highlight a research gap related to systems design methods. Finally, the gap relating to managerial complexity competency model is presented in Section 2.4.3.

2.4.1 Related to Complex Adaptive Systems Architecting

Systems architecting is a holistic system-level approach which links “what is desired” with “what is feasible” (Maier and Rechtin, 2009, pp. 8). Although researchers report challenges that occur during enterprise architecture development (in general), the literature review found that there are gaps in the description of challenges and issues facing complex adaptive systems architecting organisations. Yet, understanding these challenges is a prerequisite for devising a relevant solution to enterprise architects. While Rouse (2007) and Roos (1998) describe the fundamental areas of research for large-scale ‘complex systems’, they do not discuss the challenges the organisation that build these systems including creation of the architecture are facing –leaving room for a research opportunity in this field. Dynamic marketplace, technological evolution and variety of environments are the key drivers of future system development (Schulz et al., 2000). Thus, a good understanding of the industrial context is needed to avoid oversimplification of the problem, neglecting certain important factors and being unaware of important influences and relationships. Therefore, based on a review of literature, characterisation and generalisation of architecting challenges and issues in a complex adaptive systems context is a relevant research area.

2.4.2 Related to Systems Design Methods and Process

According to Roos (1998), studies on new approaches, frameworks, theories on system design are important and there is need for them to understand better engineering systems behaviour and design. Rouse (2007) advocate more studies on large-scale ‘complex systems’ including approaches to architecting and approaches and tools to enable decision support for those who invest in, develop, operate and use ‘complex systems’. A key challenge is creating an environment which supports context-driven, targeted information exchanges. Also of importance is an environment which enables or where design and requirements specifications are performed much closer together and in tight communication with each other (Madni, 2012). Among existing methods and design procedures discussed in

Section 2.2, there appears to be lack of simple and low cost analytical, systematic and creativity-based methods to support explicitly value robustness design concept generation and process with anticipative and creativity considerations. Creating an environment for effective negotiations and decision making is both a physical and a conceptual challenge (Rhodes and Ross, 2009). This provides an opportunity to contribute to the existing portfolio of procedures and approaches. This thesis will focus on techniques to support system design by humans as opposed to artificially intelligent machines. The approach proposed in this thesis will be simple and something that small research groups, organizations or even individuals can apply without years of training.

The reviewed design methodologies and processes in Section 2.2 were either focusing on engineering design domain (i.e., emphasising the sequence of stages through which the project is expected to progress) or the architectural design domain (i.e., emphasising the cycle of cognitive processes that the designer is required to perform). The methodology proposed and demonstrated in this thesis will be a hybrid approach.

2.4.3 Related to Managerial Complexity Competency Model

Many different fields use different approaches to enhance anticipatory practice. There is a community (e.g., Rhodes and Ross, 2009) interested in developing new competencies which are essential to establishing anticipatory capacity in engineering organisations engaged in the design of complex adaptive systems. For organisations to establish anticipatory capacity, new competencies are needed, including competency for program management complexity (Levin and Ward, 2011). Xia and Lee (2004) state that “there are no well-defined frameworks in the literature that can be used to systematically describe the key dimensions and characteristics of [managerial] complexity” (p. 71). We argue that this lack of conceptualisation provides an opportunity for theory building, with a view to understanding what might constitute an appropriate organisational response to managerial complexity. This thesis will contribute to that research agenda by deriving a managerial complexity competency model. The required knowledge and skills will be derived from a phenomenological study of project leaders’ lived experiences. Further, this research is consistent with the complex adaptive systems research agenda discussed by Rouse (2007). Rouse discusses the challenges associated with complex systems, including:

- The full design objectives for such systems;
- Approaches to architecting and modelling systems relative to these objectives;
- Methods and tools for model development and use;
- Means of evaluating and experimenting with models and real systems;

- Approaches, technologies and tools to enable decision support for those who invest in, develop, operate and use complex systems.

Designing and architecting value robust systems requires methods and competencies for exploring the concept design tradespace not just for known requirements, but in considering possible dynamic futures where context changes and/or new needs arise.

2.5 Chapter Summary

The literature reviewed in this chapter has drawn from a range of studies. Research gaps were identified based on the area of interest and following the identification, this chapter also defined the research opportunity that will be pursued in the rest of this thesis. In turn these gaps have subsequently informed the primary research questions and objectives stated in Section 1.3. It is intended that addressing these questions and objectives will provide the complex adaptive systems design research community and other communities utilising this and similar design approaches, with new knowledge and insight concerning the process of complex adaptive systems conceptual design and managerial complexity competencies.

The following chapter will discuss the methodology to be employed for this research to answer the research questions and objectives.

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CHAPTER 3 RESEARCH METHODOLOGY

This chapter addresses the first of the seven research objectives introduced in Section 1.3. All research is based on some underlying philosophical assumptions about what constitutes 'valid' research and which research method(s) is/are appropriate for the development of knowledge in a given study. In order to conduct and evaluate any research, it is therefore important to know what these assumptions are. This chapter discusses the philosophical assumptions and also the design strategies underpinning this research study.As Mitchell and Jolley (1984) point out, research begins with questions; questions for which the researcher does not have an answer. The biggest challenge is therefore choosing method(s) of investigation most likely to yield a reliable foundation for finding an answer – if there is one. The research questions have been defined, the purpose has been discussed and this section looks at how this links with the remaining two, the theoretical perspective and research design. The first section highlights the overview of the systems approach. Following this, the research methods and process are presented in relation to the different studies conducted. Finally, the research quality in terms of validity and reliability is discussed.

3.1 Planning of the Research Strategy

A research approach for a scientific inquiry can be defined as following a research strategy in which a set of research instruments are employed to study the research subject, guided by a certain research philosophy (deVreede, 1995). In the context of research, as well as in other contexts, strategy means making choices. The planning of the research strategy in this thesis is based on the various research objectives and the interconnections between them.

Insights from literature indicate that many categorisations of research have been created. For instance, there are categorisations by research philosophical paradigms, purpose and by approaches. In this thesis, the research carried out is a combination of different philosophical paradigms, purposes and approaches to categorisation. The research strategy provides a framework for designing a systematic study that addresses the goals, objectives and questions formulated in this thesis.

The following sections summarise the overall study design, activities and the extent of data resulting from this approach. Figure 3-1 presents the study's design. The design reflects the logical flow from the preliminary activities that initiated the research and the development of the design methodology through the data collection and analysis. To define these logical steps in this thesis, we are guided by the various research objectives and the interconnections between them. Establishing trustworthiness for the research was an ongoing process.

1. Preliminary activities – Problem analysis
    - To justify and initiate the research, the researcher conducted an extensive literature review of previous research on complex adaptive systems development, theoretical frameworks and methodologies appropriate to the research. The review corroborated the need for this research and provided support for the initial design methodology.
    - Conducted an exploratory Delphi study with complex adaptive systems architecting experts that confirmed the need for research on this topic and assisted the researcher in identifying an initial list of challenges and issues related to complex adaptive systems design methodology and managerial complexity control model.
    - Incorporated the researcher's knowledge and assumptions about system architecture, design theories and complex system analysis into the study design.

2. Development of three faces of the complex adaptive system conceptual model – the researcher proposed a conceptual model based on a review of the literature and the researcher's experiential knowledge to serve as a guiding framework for subsequent studies.

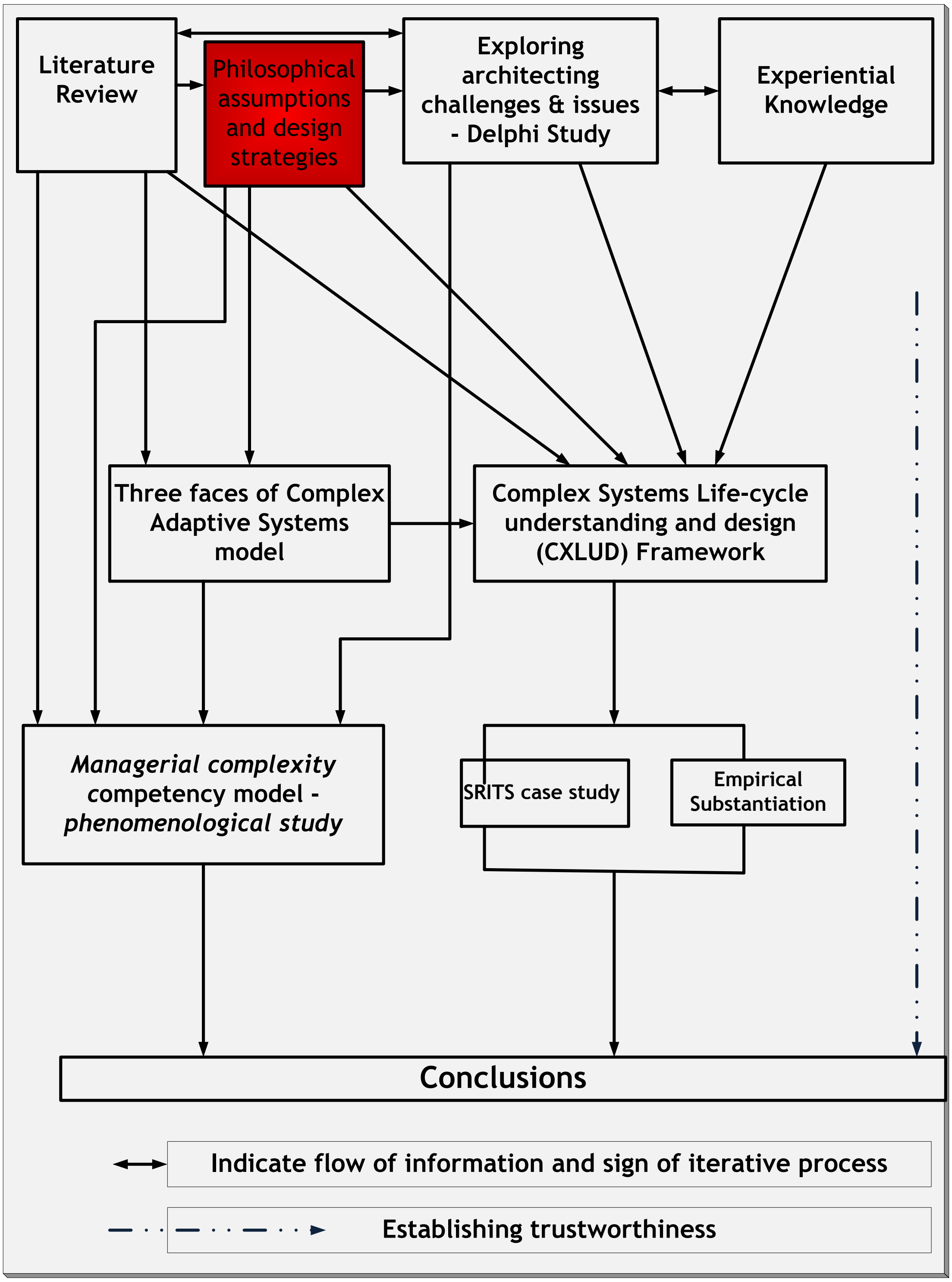

Figure 3-1: Research process with current stage highlighted (Source: Author)

3. Develop the CXLUD Framework as an organised system design enabling environment that stimulates creativity and innovation for engineering organizations seeking to define value robust systems conceptual design. The approach emerges from the analysis of real industrial problems in combination with a theoretical investigation.

4. Provide a proof-of-concept to the viability of the CXLUD methodological environment as an effective systems conceptual design method. This objective will be achieved by applying the CXLUD approach to a selected industrial case study.

5. Provide an empirical substantiation of the goodness and completeness of the CXLUD approach. This objective will be achieved by eliciting feedback from industrial experts about the framework.

6. Development of a phenomenologically informed competency model: Empirical phenomenology suggests that scientific explanation must be grounded in the first-order construction of the actors; that is their own meanings and words. A phenomenological study from the perspective of the systems architecting project managers was investigated to draw conclusions on how insights from complexity science could inform managerial complexity practice.
7. Final thesis report – the researcher compiled the results of all research activities into this document.

3.1.2 Framing the Purpose of the Research

Research may be classified on the basis of its purpose. Thus, there are a lot of alternatives when choosing a research strategy. Yin (2009) mentions three different types of purpose for research namely *exploratory, descriptive and explanatory*, where each is a way of collecting and analysing empirical evidence following its own logic. Exploratory research aims at finding out what is happening, seeking new insights and generating ideas and hypotheses for new research (i.e., it aims at generating basic knowledge and demonstrates the character of a problem by collecting information through exploration). Descriptive research involves examining a phenomenon to define it more fully or to differentiate it from other phenomena. It portrays a situation. Explanatory research is conducted to create an understanding of different conditions and events. It seeks an explanation of a situation or a problem, mostly but not necessarily in the form of a causal relationship. According to Martella et al., (1999), an explanation of a phenomenon requires knowledge from the other two purposes of research and to explain a phenomenon, researchers must first explore it and then describe it to be able to change the direction of the phenomenon. According to Yin (2009), the more appropriate view of these different purposes of research is that researchers can use each strategy for all purposes. To fulfill the various research objectives of this thesis set out in Section 1.3: exploratory, descriptive and explanatory approaches were considered relevant and are used in combination. In the next section, we expand our discussion on this thesis research methodology with details of underlying assumptions about what methods are valid and appropriate.

3.2 Philosophical Underpinnings

Any research is based on some underlying assumptions about what methods are valid and appropriate. All research is based on fundamental assumptions about the nature of the world and sources of knowledge about it. Different people make different assumptions about scientific truth. The end of specification or definition of the research question(s) and the selection of research methods are normally followed by a consideration what to accept as valid answers. The decision of whether to conduct research in the field or experiments conducted under controlled laboratory conditions reflects major differences in opinion over the nature of truth and how we arrive at it through scientific investigation. These assumptions are often referred to as the research philosophy, worldview, or paradigm. By that is meant a set of beliefs that guide the research and lead to the embracing of a qualitative, quantitative or mixed method approach in specific research work. Four dominant research philosophies can be characterised (Creswell, 2008):

1. Positivitism -positivists are reductionist, in that they study things by breaking them into simpler components. This corresponds to their belief that scientific knowledge is built up incrementally from verifiable observations and inferences based on them. The primary purpose of such studies is to test theory and researchers come to the field with a well-defined set of constructs and instruments with which to measure the social reality. The positivist researcher believes that there is a unique, best description of any chosen aspect of the phenomenon.

2. Pragmatism **-** acknowledges that all knowledge is approximate and incomplete, and its value depends on the methods by which it was obtained. Knowledge is judged by how useful it is for solving practical problems. Put simply, truth is whatever works at the time. This stance therefore entails a degree of relativism: what is useful for one

person to believe might not be useful for another; therefore truth is relative to the observer. A researcher should be free to use whatever research methods shed light on the research problem. Pragmatists use any available methods and strongly prefer mixed methods research, where several methods are used to shed light on the issue under study.

3. Constructivism **-** this is also known as interpretivism (Klein and Myers, 1999). It rejects the idea that scientific knowledge can be separated from its human context (Klein and Myers, 1999). Interpretivists concentrate less on verifying theories and more on understanding how different people make sense of the world and how they assign meaning to actions. Interpretivists prefer methods that collect rich qualitative data about human activities, from which theories might emerge. Interpretivism is most closely associated with ethnographies, although interpretivists often use exploratory case studies and survey research too (Easterbrook et al., 2007). Constructivists prefer methods that collect rich qualitative data about human activities, from which local theories might emerge.

4. Critical Theory - critical theory argues that reality is "shaped by social, political, cultural, economic, and ethnic and gender values". Critical theorists prefer participatory approaches in which the groups they are trying to help are engaged in the research, including helping to set its goals. In Software Engineering, it includes research that actively seeks to challenge existing perceptions about software practice, most notably the open source movement, the process improvement community and the agile community (Easterbrook et al., 2007).

All of these philosophies have been used in Systems Engineering and Complexity Science research, offering insightful perspectives on phenomena. While some scholars suggest that a researcher should strictly use one of these paradigms in a single study, others argue that one can combine them within different phases of a single study (e.g., Gable, 1994; Kaplan and Duchon, 1998). Yet another group of researchers (e.g., Lee, 1991) argue that while the different categories may be philosophically different, it is hard to see their differences when put in to practice. It is obvious from the analysis of the literature review that individual researchers may be influenced by their various institutional contexts and training when trying to answer the question, "which approach is best to use?" Yet, it is a critical element that has to be addressed early on in a study design. The selected approach (or approaches) dictates the researcher to focus attention on certain aspects and not on others and will influence the whole research methodology. In this thesis, we subscribe to the position taken by (Lee, 1991) that many useful approaches from all these philosophical views can be combined together in the actual detailed research plan of a study; the research drew a great deal of strength from the constructivism paradigm. This implies that realities are locally constructed, depending on the views of specific actors or groups and concentrate less on verifying theories and more on understanding how different people make sense of the world and how they assign meaning to actions.

3.3 Reasoning Approach

It is commonly accepted that in scientific inquiry, we use three basic forms of reasoning by which we draw conclusions on matters of importance: we argue for a case, we make generalizations, and we construct explanations and interpretations. Conventionally, deduction, induction and abduction have been considered the three basic forms of scientific reasoning, or as Elalfi et al., (2009) state, a reasoning style. This entails the process of using existing knowledge to draw conclusions, make predictions or construct explanations.

Induction, deduction and abduction as they are generally called are used constantly by researchers and scientists. According to Graziano and Raulin (2010), with deductive reasoning, the construct is used as a basis for making predictions about new, specific observations; i.e., deductive reasoning begins from a base of theoretical knowledge, derives new theory from this background and uses empirical testing to support conclusions to accept or reject the new theory.

The combination of both induction and deduction generally called abduction is what characterises science (Graziano and Raulin, 2010). At the stage of abduction, the goal is to explore data, find a pattern and suggest a plausible hypothesis. From the point of view of reasoning practice, abductive reasoning is one of the primary reasoning tools we use, both in mundane decisions and in scientific inquiry (Lipton, 2004). Abductive reasoning is therefore defined as the combination of inductive and deductive reasoning. This means that an approach is developed using deductive reasoning, followed by testing with the use of inductive reasoning (Samuels, 2000). Inductive reasoning supports development of new theories and deductive reasoning supports explaining specific cases based on the existing theories; abductive reasoning supports delivering new things (Lindström, 2010). According to Thagard and Shelley (1997), unifying conceptions are an important part of abduction and abduction shows how something might be (Curry et al., 2009).

In fact, the abductive approach is applicable for cases which entail conditions for both inductive and deductive reasoning. In this thesis, the abductive approach was followed. This approach was selected based on the aims of the various research objectives. Research objective 2 is translated to mean look for a pattern in complex adaptive systems characteristics and suggest a plausible abstraction (presented as three faces of complex adaptive systems model in Chapter 8). Accordingly, the abductive approach was found to be a suitable choice. This is because abductive reasoning entails looking for patterns in a phenomenon and suggesting plausible hypotheses.

Another objective of this thesis was developing a new artifact for effective complex adaptive systems conceptual design (the CXLUD framework presented in chapter 5). The initial results were required to be evaluated (validated). Results of this validation are presented in Chapter 7. Accordingly, the abductive approach was found to be a suitable choice for the purpose of this research because the development of the CXLUD framework was guided by the elements of generality to extract a proper mode of perception (see Chapter 5). This is a major characteristic of abductive reasoning.

Another objective of this thesis was development of a new managerial complexity competency model (as presented in Chapter 8). To achieve this, the research began with a qualitative phenomenological study of lived experiences of project leaders to derive the required criteria, i.e., knowledge, skills for success. Abduction reasoning is very appropriate for this research objective because it entails beginning with the details and building up a picture of the whole as it emerges from the particulars. An alternative interpretation is that the research began with expectation and seeks for, or shapes phenomena that match the expectation. In the research, the process started with a proposal of the ‘three faces of complex adaptive systems conceptual model’, followed by an analysis of the derived thematised constructs from the lived experiences data to map to the conceptual model. Accordingly, the abductive approach was found to be a suitable choice for the purpose of this research.

Abduction occurs when individual phenomena is interpreted or re-contextualised from the perspective of a new conceptual framework – a true reflection of the process this thesis has taken in developing the managerial complexity competency model (see Chapter 8).

3.4 Qualitative versus Quantitative Methods

Although there are other distinctions in a research sense, the most common classification of research methods is into *quantitative* and *qualitative*, or a combination of the two generally referred to as *mixed* methods research (Creswell and Plano Clark, 2007). There are different schools of thought on what each really represents or is best at. Alvesson and Sköldberg (2000) point out that an important distinguishing attribute is that a qualitative approach starts from the perspective and actions of the studied subjects, whereas quantitative studies proceed from the researcher's ideas about the dimensions and categories that should be focused on. Most pragmatists believe that the truth is what works at the time and requires that researchers or investigators use both quantitative and qualitative methods to provide the best understanding of a research problem (Patton, 2002). As shown in Table 3-1, Burns (2000) has identified and effectively compared key research methods used in both approaches.

Table 3-1: Comparison of Qualitative and Quantitative Research Strategies (Burns, 2000)

Qualitative	Quantitative
Assumptions	
Reality socially constructed	Facts and data have an objective Reality
Variables complex and interwoven; difficult to measure	Variables can be measured and Identified
Events viewed from informant's perspective	Events viewed from outsider's Perspective
Dynamic quality to life	Static reality to life
Purpose	
Interpretation	Prediction
Contextualisation	Generalisation
Understanding the perspectives of others	Casual explanation
Method	
Data collection using participant observation, unstructured interviews	Testing and measuring
Concludes with hypothesis and grounded theory	Commences with hypothesis and Theory
Emergence and portrayal	Manipulation and control

Inductive and naturalistic	Deductive and experimental
Data analysis by themes from informants descriptions	Statistical analysis
Data reported in language of informant	Statistical reporting
Descriptive write-up	Abstract impersonal write-up
Role of researcher	
Researcher as instrument	Researcher applies formal Instruments
Personal involvement	Detachment
Empathic understanding	Objective

3.4.1 Researching Qualitatively

A suitable research approach for the study of complex adaptive system conceptual design and managerial complexity competency model acknowledges the complexity of both technical and social processes and focus on both the context and specifics of the required model development. The researcher concluded that a qualitative research approach oriented towards discovery, description and holistic understanding of processes and activities was a suitable option. n this section, we identify some basic assumptions of a qualitative study and link them to the studies presented in this thesis. Linking the assumptions to the specific character of the research carried out (Table 3-2) demonstrates that a qualitative research approach was appropriate for this thesis. The result is that the research design allows the researcher to pursue new directions in data collection as understanding developed during the research.

Table 3-2: Linking the assumptions to the specific character of the research

Assumptions	This thesis study
Qualitative research enables a holistic perspective	Qualitative research assumes that a whole phenomenon is under study and that a complex adaptive system cannot be meaningfully reduced to several variables and linear causal relationships.
Qualitative research incorporates an emergent design:	This fact was considered and met in writing this thesis. The research design cannot be completely specified in advance of fieldwork. Understanding develops and evolves through the research process and each data collection and analysis activity informs subsequent data collection and analysis activities. The exploratory part of this study required flexibility to respond to the researcher's evolving understanding and to pursue new

	avenues of inquiry as needed.
Qualitative research is descriptive	Qualitative research focuses on describing and understanding a phenomenon. The goal of the research results presented in Chapter 4 (CIRD conceptual model involves describing and understanding complex adaptive systems architecting challenges and issues phenomenon) and Chapter 8 (UPA competency model focuses on describing and understanding skills, abilities and knowledge required to be successful in managerial complexity control) .
Qualitative research involves fieldwork	Fieldwork implies that the researcher has direct and personal contact with the people involved in a phenomenon and in the natural setting of the phenomenon. The researcher conducted fieldwork with participants involved in the complex adaptive systems architecting (presented in Chapter 4) and managerial complexity control (presented in Chapter 8) to understand the phenomenon in its natural setting.
Qualitative research uses the researcher as the primary instrument for data collection and analysis	Qualitative research assumes that data can be mediated directly by researcher rather than through questionnaires, surveys, etc. In this study, the researcher collected data through examination of documentary evidence (e.g., Delphi study and SRITS case study reported in Chapters 4 and 6, respectively rely on documentary evidence as part of the data collection methods), written interviews with participants and observations (e.g., Delphi study, SRITS case study and the phenomenological study reported in Chapters 4, 7 and 8, respectively rely on written interview and observations as part of the data collection methods).
Qualitative research is interested in how people interpret their experiences and how they structure their socio-technical views	Complex adaptive systems design and management framework development is a social process in which a variety of stakeholders come together to contribute ideas on one or more ways of doing something. This study directed attention to the individuals and their perceptions, values and interpretations. The Delphi study and the Phenomenological study reported in Chapters 4 and 8 respectively are such cases.
Research is primarily concerned with process rather than outcomes	Qualitative research focuses on processes and is interested in understanding and describing dynamic and complex processes. The study reported in Chapter 5 (i.e., creation of CXLUD Framework) was concerned with 'what' and 'how' questions about stimulating creativity and innovation in complex adaptive system conceptual design.

3.5 Research Instrument Choice

The choice of research instruments are known to have some consequences on research conclusions. Based on previous discussion, combinations of 'literature analysis, case study, and phenomenological study and Delphi study' were selected for the research methods. In the next sections, we further make the case for the choices of research instruments used and this is discussed under ‘Case Study,’ ‘Phenomenological Study’ and ‘Delphi Study.’ The relevant research processes implemented for each approach are also discussed and justified.

3.5.1 Case Study Approach

3.5.1.1 What is a Case Study?

Case studies appear to be defined in various ways and a standard does not exist. There are a number of important articles describing the case study approach to research that we refer to. Based on a review of case study definitions from a number of sources, Benbasat et al., (1987, p.370) stated that “a case study examines a phenomenon in its natural setting, employing multiple methods of data collection to gather information from one or a few entities (people, groups or organizations). The boundaries of the phenomenon are not clearly evident at the outset of the research and no experimental control or manipulation is used.”

Case study method is considered by Benbasat et al., (1987, p.370) to be viable for three reasons:

- It is necessary to study the phenomenon in its natural setting;
- The researcher can ask "how" and "why" questions, so as to understand the nature and complexity of the processes taking place;
- Research is being conducted in an area where few, if any, previous studies have been undertaken.

Case studies require multiple data collection methods, whose results hopefully converge, in order to establish construct validity. Yin (2003a) identifies these methods as including:

- direct observation of activities and phenomena and their environment;
- indirect observation or measurement of process related phenomena;
- interviews - structured or unstructured;
- Documentations in form of written, printed or electronic information about the company and its operations; also newspaper cuttings.

Two types of case study are described in (Yin, 2003b). They are: Single Case: It examines a single organization, group, or system in detail; involves no variable manipulation, experimental design or controls. Multiple Case Studies: They are as for single case studies, but carried out in a small number of organizations or context. Multiple case studies were not undertaken in this research.

3.5.1.2 Case Study Suitability for this Research

A case study approach was selected for the research studies as indicated (in this thesis) because it offers a better approach to work closely with a company or to test for instance a design procedure of interest. Asking "how" and "why" questions will help us to understand the nature of the processes, while asking "how to" questions will assist us in interpreting the data we collect and to improve the proposed system design methodological approach and design procedure whose usage we are facilitating. The case study approach allowed the researcher to take on the role of a facilitator and observer but avoid becoming a direct participant as far as is possible, restricting the researcher to meeting process dynamics. To clarify further, the researcher is the driver of the solutions (CXLUD Framework), but not the manager of the meetings. Thus, there is limited control over behavioural events. No attempt is being made to change the behaviour of the participants.

As pointed out by (Wohlin, 2000), real-life case studies are suitable for an industrial evaluation of software engineering techniques and tools if they are organized and conducted in a sound way. This is exactly the case in this thesis as presented in SRITS case study (Chapter 6) and substantiation study (Chapter 7). In both studies, specific purposes and objectives of the studies were properly set out and participants involved fully understood what was expected of the study and processes involved. Also from a social organisation viewpoint, the study of a newly invented technique/method is impossible without intervening in some way to inject the new approach into the practitioner's environment. The decision making in complex adaptive systems is an all-pervading activity (Sarma, 1994). Given this definition, a general reason for doing a case study research is to understand the process of complex phenomena and the outcome better; i.e. a rewarding way to learn and to improve practice. In addition, Stake (2000, pp. 436) notes that a “case study is both a process of inquiry about the case and the product of that inquiry,” namely the thesis.

3.5.2 Phenomenological Study Approach

3.5.2.1 What is a Phenomenological Study?

The purpose of a phenomenological study is “to understand an experience from the participants’ point of view” (Leedy and Ormrod, 2001, p. 157). According to Johnson

(2002), the fundamental question of a phenomenological study is: What are the meanings, structures, and essences of the lived experience of the phenomenon by an individual or by many individuals. When using the phenomenological research approach, Lester (1999, p.2) suggest that "a variety of methods can be used in phenomenological-based research, including interviews, conversations, participant observation, action research, focus meetings and analysis of personal texts." He further explained that, "interview transcripts, unstructured notes or personal texts" are generally used when implementing this methodology and the process is to "read through and get a feel for what is being said, identifying key themes and issues in each text". According to Finlay (2009), the flexibility of phenomenological research and the adaptability of its methods to ever widening arcs of inquiry is one of its greatest strengths. (Lester, 1999) pointed out that a summary of the phenomenological findings are best arranged according to themes and topics and to draw out key issues being discussed by participants. Accordingly, key demographics that reflect the level of experience of the participants are essential to the external validity of this research study (Golafshani, 2003). Insights from literature (e.g., Moustakas, 1994) indicate that lived experience research requires that study participants have experienced the phenomenon of interest. For the research presented in this thesis, the population comprised of project leaders/managers involved in complex adaptive systems design and management. Participants were selected following a workshop on complex adaptive systems design methodology. In total, twenty one participants of the workshop responded to the interview study, but only nine of the respondents were added to the data analysis pool. The nine participants represent a wide variety of backgrounds and extensive experience in complex adaptive systems design and management. The number of participants also concur with the widely held view of what numbers are sufficient. For instance, while Creswell (2007) advocated for participants of between 5 and 25 to reach theoretical data saturation, Finlay (2009) recommend recruiting at least 3 participants. It is also important that the participant selection is purposive (Creswell, 2007). This was achieved in this thesis because individuals were intentionally selected based on defined characteristics of the phenomenon under study. The data collection was facilitated through semi-structured written interviews with the study participants. The interview questions served as the instrument tool for the research study (see Appendix E).

3.5.2.2 Phenomenological Data Analysis

Creswell (2007) notes that phenomenological data analysis is unique to each study and should be customised. During data analysis, a process called *horizonalization* was used to assemble the primary data into general units of meaning while disregarding material not applicable to the research topic (Moustakas, 1994). The data analysis process was continued by thoroughly reviewing each participant's transcribed interview checking the components for uniqueness, overlap and repetitiveness. By rigorously applying this *thematizing* procedure (Moustakas, 1994), redundant components were excluded from further consideration and only properly grouped experiences became part of the core themes. Core themes, according to Moustakas (1994), are the *invariant constituents* that result from the phenomenological reduction and bracketing process in which the descriptive essences of the participant's narrative, perceptions and experiences are constructed. More background information is provided in Appendix E.

3.5.2.3 Phenomenological Approach Suitability for this Research

The particular research question and research objective (see research objective 6 in Section 1.3) were best answered by a phenomenological approach because it facilitated the search for the meaning and nature of project manager's direct experiences through their first person accounts. The aim of the study was to discover strategies and practices that would form sets of skills, knowledge and abilities required of managerial complexity project managers which is a necessary requirement in the development of a competency model. A phenomenological study is appropriate for studying such processes because portraying the experience of process requires detailed description of how people engage with one another (Patton, 2002); the various experiences can be captured with direct quotes (Van Manen, 1990) and such processes require obtaining the perception of the participants (Moustakas, 1994; Patton, 2002).A phenomenological study is a best fit for the research objective since it focuses on how people make sense of their experiences and the world, how they develop a worldview, make sense of experience and transform experience into consciousness (Patton, 2002).

3.5.3 Delphi Study Approach

3.5.3.1 What is a Delphi Study?

According to (MacCarthy and Atthirawong, 2003), a Delphi study is a systematic, iterative process to elicit a consensus from a group of expert opinions concerning the future. The Delphi method is designed to obtain the most reliable consensus from a panel of experts by a series of intensive questionnaires interspersed with controlled opinion feedback and with results of each round being fed into the next (Chan et al., 2001). It is said that even if these collective judgments of experts are made up of subjective opinions, it is more reliable than individual statements, thus, more objective in its outcomes. The Delphi technique involves using a series of confidential questionnaires to refine a solution (Lussier, 2005). The Delphi method typically involves the selection of suitable experts, development of appropriate questions to be put to them and analysis of their answers (Cahanis, 2002; Outhred, 2001).

One of the most important considerations when carrying out a Delphi study is the identification and selection of potential members to constitute the panel of experts (Ludwing, 2001).

3.5.3.2 Delphi Study Procedure

The selection of participants is important because the validity of the study is directly related to this selection process. The participants were working for one of the largest financial institutions in United Kingdom. For confidentiality reasons, the description of the study organisation is not detailed. For simplicity, we refer to the organisation as ‘LSW’ where required. The sponsorship received (in terms of willingness to allow the researcher in a direct participant role) was the main factor that influenced the decision to select LSW for this study. The main research objective was to find out the complex adaptive system architecting challenges and issues – if any - identified by the architecting team working on designing a specific complex adaptive system.

The data collection methods consisted of four rounds. Questions in each of the first three rounds were administered through electronic mail. Each round was separately analysed and the result was used as input to the next round.

Delphi panel – First round. In the first round of the Delphi questionnaire survey, panelists were asked to list at least four challenges and issues considered important to be having significant impact on systems architecture design. An example of a possible answer was also provided as part of the question. An open-ended question format was used, since “open-ended responses permit one to understand the architecting challenges and issues as seen by the participants. The purpose of gathering responses to open-ended questions is to enable the researcher to understand and capture the points of view of other people without predetermining those points of view through prior selection of questionnaire categories”

Patton (2002, p 21). After the questionnaire was returned, all comments by the respondents were combined in order to modify the questions for another round of the study.

Delphi panel – Second round. In round 2 of the Delphi study, the panelists were provided with the consolidated results from Round 1 and were asked to provide ratings to the selected main challenges and issues (23 challenges and issues have been selected for further study based on criteria that all of them were selected by at least two of the participants).

The second round served several purposes. The first one was to validate that the challenges and issues extracted were actual problems and to see whether the different respondents agreed. Lastly, it was used as an elicitation of challenges and issues considered to be more significant and which should therefore be further analysed in the next step. It will also serve as ideas and hypotheses for new research (Runeson and Höst, 2009). According to Hsu and Sandford (2007), the second round of the Delphi is where expert consensus begins to take shape.

Delphi panel – Third round. In the third round of the Delphi questionnaire survey, mean scores were calculated for each item from the Round 2 responses using a five-point scale (1 = very important to 5 = very unimportant). Calculating the mean for 5-point likert scale data involves using Excel software formula. In simple terms, the excel formula is: =SUMPRODUCT ({1, 2, 3, 4, 5}, RANGE) / SUM (RANGE), where RANGE is the range of rows/columns where the raw data is. The mean score was marked on an importance scale for each of the items; participants were then asked to rate the accuracy of the mean scores using a three-point scale (1 = should reflect more importance, 2 = is an accurate representation of importance and 3 = should reflect less importance). The numbers are adjusted to be (1.00 – 1.49 = very important, 1.50 – 1.99 = quite important, 2.00 – 2.49 = somewhat important, and 2.50 – 3.00 = neither important nor unimportant).

Delphi panel – Fourth round. In the fourth and final round of the Delphi study, the collated challenges and issues were presented and member checked by the participants and possible solutions suggested.

Critics of the Delphi method have raised significant concerns about its use. According to Boberg and Morris-Khoo (1992), the Delphi practice of seeking several rounds of feedback, where participants can view responses of the entire group may indeed manipulate the group into consensus. Boberg and Morris-Khoo (1992) also argued that the Delphi method is highly unlikely to provide test reliability and generalisability because the identified experts are not typically randomly selected and the settings in which the study rounds are completed are not under the control of researchers.

Balancing considerations in choice of Delphi, Hasson et al., (2000) wrote that results can be used to structure discussion as well as present debatable issues. In other words, a Delphi study is best used as a tool to expose perspectives and encourage possible actions, and should not be viewed as a necessarily true current or future picture (Hasson et al., 2000). Thus, the Delphi study reported in this thesis is used as a tool to expose perspectives and encourage possible actions. This thesis research objective did not call for generalisability. In addition, the particular result of the Delphi study is not expected to be viewed as a necessarily future picture. Section 3 discusses in further details, the Delphi suitability for this research.

3.5.3.3 Delphi Suitability for this Research

The purpose of the study was to explore and identify system architecting challenges and issues. The results of the study further define the problems to be solved in this thesis. Therefore, using a Delphi technique and having committed members of the architecting team who are all considered to be experts in systems architecting fulfills one of the most important requirements in a Delphi study. The assumption made in using a Delphi method for the study concurs with views expressed by Vázquez-Ramos et al., (2007), who suggest that results garnered by the Delphi method can lead to further instrument development, as well as programs and also more ‘comprehensive’ abilities to understand the topic being studied.

Using the Delphi method allowed exploration in a real-life environment with underlying assumptions or information leading to differing judgments in design methodology development. It has also afforded the opportunity to correlate informed judgments on a complex adaptive system architecting project. Such objectives according to Turoff (1970) can be pursued successfully using a Delphi method. An additional reason for using the Delphi method concurs with the views expressed in (van Zolingen and Klaassen, 2003) that the Delphi method is a qualitative, long-range forecasting technique to elicit, refine and draw upon the collective opinion and expertise of a panel of experts. The research viewed the Delphi technique as a useful approach to investigate and understand the factors that influence or may influence decision making on a specific issue, topic or problem area. This is also pointed out by (MacCarthy and Atthirawong, 2003).Using the Delphi method utilised the knowledge of experts, combining it and redistributing it, which forces new thought processes to emerge. It also allows participants to see how closely they responded to the rest of the field of experts and to justify their train of thought. This same position was also argued in (McKillip, 1987).

Finding out the challenges and issues facing a systems architecting organisation is a problematic design problem. A good understanding of the industrial context is thus desirable in order to avoid oversimplification of the problem, neglecting certain important factors and being unaware of important influences and relationships. Using the Delphi method in this study has enabled the researcher to achieve the following: 1) development of a range of responses to a problematic issue; 2) the ranking of a range of responses in order to provide an indication of significance; and the 3) establishment of consensus regarding a range of responses. These provide answers to one of this thesis' particular research objective discussed in Section 1.3.

3.6 Total Quality and Trustworthiness of the Study

A fundamental concern in any research study is to incorporate appropriate mechanisms that assure the researcher and reader of the quality of the research, its process and its findings. The trustworthiness of findings from flexible, qualitative research has been the subject of much debate (Robson, 2002). However, the assumptions and characteristics of qualitative inquiry as a research paradigm suggest a set of criteria for establishing quality. According to Priest (2002), researchers must exercise rigour to ensure qualitative research is believable, accurate and right and useful to people beyond those who participate in it. Lincoln and Guba (1985) argue that appropriate criteria for trustworthiness in qualitative research are credibility, transferability, dependability and conformability. Following Lincoln and Guba (1985, pp. 289-331), this thesis addressed quality in terms of trustworthiness related to these criteria:

Credibility

Credibility is the substitute for internal validity and denotes that the reconstructions, i.e., the outcome of the research process, are "credible to the constructors of the original multiple realities" and that the inquiry is carried out in a trustworthy way (Lincoln and Guba, 1985, p

296). This means that the persons in the case should recognise the reconstruction. For instance, the interviewees should recognise our description of the managerial complexity competencies (i.e., results of phenomenological study presented in Chapter 8) or the CIRD model (i.e., the conceptual model of architecting challenges and issues presented in Chapter 4), although they have not explicitly discussed them in these terms during the studies. They should feel comfortable with our interpretations and conceptualisations. In both the Delphi and phenomenological studies, we verified the results using member checking. The results were found to be credible by the persons who participated on those two occasions. Internal validity is 'only a concern for causal (or explanatory) case studies' (Yin, 2003). Our case study and the Delphi study are explorative and hence less sensitive to the internal validity which is only a concern for causal (or explanatory) case studies.

Transferability

Transferability is related to the concept of Yin's external validity (Yin, 2003). Lincoln and Guba (1985) argue that in a strict sense it is impossible to reach external validity. Instead, the researcher has to provide a detailed description of the context in which a working hypothesis is found to hold. The transferability is then connected to the degree of correspondence between the sending and receiving contexts. While the sending context is the case from which the conclusions are made, the receiving context is the case that may use the results. Moreover, the judgment of transferability lies with the person who wishes to use the results (Lincoln and Guba, 1985). This means that we should provide information that facilitates an assessment of the transferability. To facilitate the assessment, we described the research context of the Delphi study, case study, phenomenological study and in each of the studies; discussions were carried out with participants to get indications of the transferability. At the end, we can conclude based on those discussions that the decision situations of decision-makers in the outcomes of these separate studies (i.e., CIRD Model, CXLUD framework and managerial complexity competency model) are not unique and have transferability potentials. Further studies are needed in order to draw certainty conclusions. For this reason the scope and the context of the research was precisely defined.

Dependability

There can be no credibility without dependability. In our research, we are assured of dependability by giving a careful account of the research processes and the methodological considerations. Lincoln and Guba (1985) propose using techniques with regard to dependability such as overlap methods and inquiry audit. The overlap methods technique is a type of triangulation and has been used in this research project. The technique inquiry audit is concerned with examining the research process and the research product.

Conformability

The last of Lincoln and Guba’s (1985) quality criteria is conformability, which is the qualitative term for objectivity. Conformability is not concerned with the objectivity of the researcher; instead, the focus is on the quality of the report. It has been our intention to be transparent and achieve traceability when reporting the process and the findings. We tried to elaborate the details of our research process in order to facilitate an audit of the process. We also frequently provided quotations from the empirical data, so that it to some extent should be possible to assess our interpretations of the data. Thus, we consider the results to be conformable with their empirical origin and that it is possible to judge the conformability from our report. In summary, Table 3-3 describes in more details the steps the researcher took to build a foundation for trustworthiness and quality in this thesis.

Table 3-3: Describe steps the researcher took to build a foundation for trustworthiness and quality in this thesis

Steps	Descriptions
Quality of data sources	The researcher was keenly aware throughout the research that high-quality data was the foundation upon which to document and build an understanding of complex adaptive system research and design. Several procedures assisted in collecting appropriate and high quality data. For the documentary evidence, the researcher used primary source materials from established peer reviewed journals, conferences proceedings and books. Official records such as program reports from the Delphi and Case study industrial partners provided the researcher with authoritative data upon which to document the CIRD conceptual models (Chapter 4) and case study result (Chapter 6). Another procedure used for ensuring authoritative data was purposeful sampling of individuals for the Delphi study, Case study and the Phenomenological study. All the participants in these studies are taken to be experts and knowledgeable in the various subjects studied. The final primary source of collected data was the researcher participant observation of the Delphi study and CXLUD case study sessions.
Analysis of	Several procedures assisted in analyzing the data to ensure credibility and

data and development of findings	dependability of the data and findings. 1. Triangulation: the researcher used multiple sources of data and several methods of data collection. Triangulation enables the researcher to find corroborating evidence in the different sources of data to ensure the accuracy of facts and interpretations. 2. Documenting methods and methodological choices: at the outset of the research, the researcher prepared a systematic design to guide the research. The design focused on multiple sources of data, appropriate data analysis activities and a preliminary complex adaptive system architecting challenges and issues to frame the research. 3. Grounding findings in data: the study's method of iteration between data collection, analysis and synthesis directed the researcher to move between data, coding, findings and back to the data. Thus, the objective of ensuring that the data supported the findings and conclusions arrived at by the researcher was achieved.
Assessing the accuracy and credibility of findings and conclusions	Qualitative research assumes that data collection; data analysis and research findings are mediated by the researcher. The member checks (i.e., empirical validation study) presented in Chapter 7 served as a useful procedure to check the credibility of the results and protect the conclusions from the researcher constructions that did not reflect the phenomenon adequately or accurately. A member check in this thesis is a procedure in which the researcher returns to participants in the study to discuss with them the researcher's emerging and evolving understanding. In addition, accuracy and credibility of findings and conclusions were also established by exposing the process and results of our research through publishing and presenting in peer reviewed conferences (e.g., Amaechi and Counsell, 2012a; 2012b; 2012c).

3.7 Chapter Summary

This chapter has outlined the research paradigm, research methodologies, strategies and design used in the study, including procedures, data collection tools, data collection and analysis methods and data credibility issues. The choice of appropriate research method is dependent upon the research problem. The nature of the research problems made it suitable to use a qualitative research method. The research process was conducted in different steps. We place our research in both the pragmatist and the interpretivist philosophical camps, utilising a mixture of Delphi, Case study and phenomenological methods. These methods serve exploratory, descriptive and explanatory purposes.

The decisions to adopt qualitative research methods as opposed to quantitative methods were discussed and justified. The choices and suitability of the Case study, Delphi and Phenomenological research methods were discussed and justified. The research methods were considered appropriate, since they made it possible to adequately address the research questions and objectives. The choice of abduction as a particular reasoning approach was also discussed and justified. We consider the results to be trustworthy, since credibility, transferability, dependability and conformability have been taken into account during the research process as well as in the report of process and findings. Following the delineation of the research design, Chapter 4 will provide details of the implementation of research objectives 2 and 3.

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CHAPTER 4 CHARACTERISATION OF COMPLEX SYSTEM DESIGN AND ARCHITECTURAL CHALLENGES

This chapter addresses the second and third of the six research objectives introduced in Section 1.3. The goal of the second research objective is to conceptualise and operationalise complex adaptive system concepts for subsequent analysis. This section attempts to understand complex adaptive systems. Every complex adaptive system has an architecture. Architectures may arise in the process of deliberate *de novo* design of a system; or by exploration of form and behavioural requirements via dialogue between users and architects, to name a few known mechanisms.

In Section 4.1, we discuss the development of the ‘three faces of a complex adaptive system’ conceptual model; a theory and knowledge development obtained by exploration and rational comprehension. Based on this, ‘three faces of a complex adaptive system’ taken as a framework of reasoning was constructed. This study is motivated by research objective 2. One of the uses of an exploratory study is to gain a preliminary understanding of a topic, particularly when it lacks a body of research to inform. Section 4.1 uses principles or systems properties to describe or to explain complex adaptive systems.

To tie the research focus to the “state of the practice,” an exploratory Delphi study was conducted with industry based systems engineers to gain their insight into the challenges and issues of complex adaptive system architecting. In Section 4-2, we present the results of an exploratory Delphi study. This study is motivated by research objective 3 and the results are presented in this thesis as the CIRD model. The Delphi study demonstrates that a good understanding of the industrial context is needed to avoid oversimplification of the problems, neglecting certain important factors and being unaware of important influences and relationships. These insights serve to ground the other research described in this thesis to practical limitations, while gaining empirical knowledge. This part of the Chapter is based on (Amaechi and Counsell, 2012b).

Figure 4-1 shows how this Chapter fits into the overall research process.

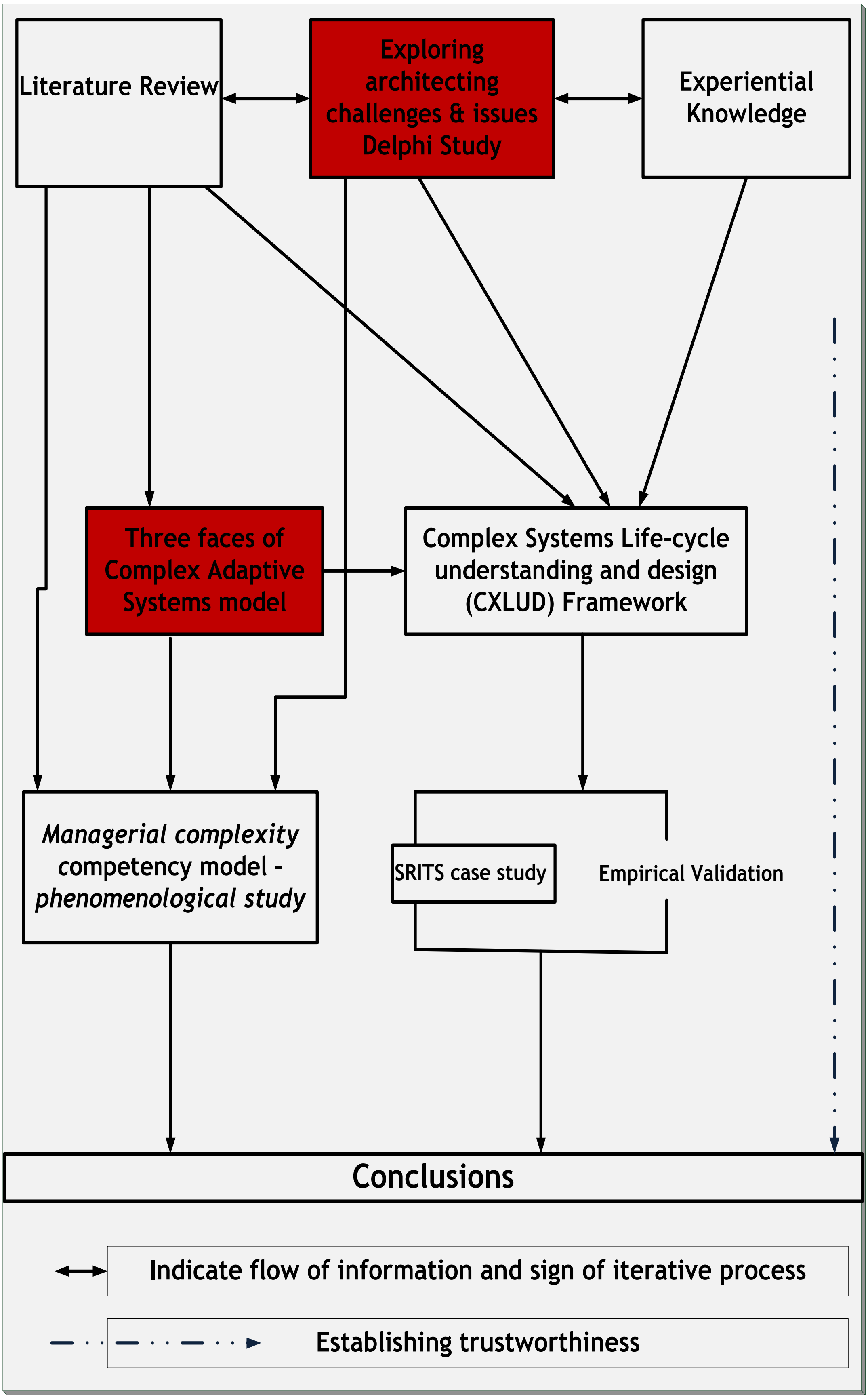

Figure 4-1: Research process with current stage highlighted

4.1 Three faces of Complex Adaptive Systems

Complex adaptive systems theory has been used in many disciplines to describe and better understand the features, mechanisms and rules of complex phenomena. Insights from literature indicate that there is no single good definition of Complex Adaptive Systems. As Ottino (2004) stated, despite significant recent advances, the field is still in flux. Consequently, many contributors defined complex adaptive systems by describing their main characteristics and principles. In this section, a generic decision situation model of complex adaptive systems is proposed. Our working definition of a decision situation is that it is a contextual holistic view of related aspects that concerns a decision-maker – as a subsystem that can form requirements and makes decisions. Our working definition of a Complex adaptive system is that it is an open system in which different elements interact dynamically to exchange information, self-organise and create many different feedback loops, in which relationships between causes and effects are non-linear and where the system as a whole has emergent properties that cannot be understood by reference to the component parts. The Complex adaptive systems principles specify that the conceptual model should be flexible and have a structure that permits frequent reconsideration and redesign, because the understanding, definition and objectives of the complex situation is constantly changing. The conceptual model in Figure 4-2 is the result of a thorough analysis of decision-making and design activities literature.

Complexity has been perceived:

1. As a problem encountered in practicing design or understanding and representing design processes and products.
2. As a characteristic attribute of design systems and artifacts.
3. As a methodology and tool for designing.
4. As a theory for understanding and defining design.

Thus, links between complexity and design can be classified in different ways. Although there are various views and definitions of design, design researchers generally agree that design is a natural activity, inherent in many of human endeavours, from architecture and engineering, to software and product design. Design is a synthetic, productive process which aims at the creation of some new artifact to satisfy goals and intentions that are themselves subjects of the process. At its core, design requires foresight. The designer must anticipate responses and outcomes. Thus, the existence of complexity creates a problem for design: by definition, complex adaptive systems are difficult to design and anticipate.

The human decision maker, as an intelligent subsystem that forms requirements and makes decisions in complex adaptive systems has been identified as a source of managerial complexity for designers of CAS. A new conceptual model, 'three faces of complex adaptive system' *(Understand - Perception - Action Taken),* is proposed to capture the decision maker relationships between analyzing, designing and managing the systems. The 'three faces of complex adaptive system' is specifically built on top of the principles of Simon's (1977) breakdown of the design activity; i.e., the definition parallels Simon's conceptualization of design activities which "involves a relation among three terms: the *inventing*, the *developing*, and the *possible courses of action* in which the artifact performs" (Simon, 1977). Therefore, the conceptual model stands for the three phases which occur when a human, as an intelligent sub-system attempts to change a complex adaptive system. The dynamics among these three factors determine the perceived success of the system. These of course, are not necessarily clear cut categories; many studies focus on questions that traverse these boundaries and results and insights from one area normally influence the others. The 'three faces of complex adaptive system' conceptual model is presented in Figure 4-2. These three levels of purposes are not mutually exclusive with regard to complex situations study or evaluation methods, but they may be needed at different times.

Simon explains the emergence of hierarchical structure as a natural outcome of processes in which the evolving elements of a complex design are limited in their capacity to interact with each other. The cognitive limitations of human designers, for example, favour systems that can be decomposed into nested subsystems and produced by organizations with a similar modular structure.

On the first level, we find the complex adaptive systems sub-theories or characteristics which facilitate understanding and observation of a complex adaptive systems design problem and environment. The level describes the characteristics making it possible to understand complex adaptive systems phenomena. The 'understand' level suggests that whoever develops a level of system understanding prior to acting will be more successful in dealing with complex adaptive system problems.

The second level 'perception' allows the identification of any certain universal mechanisms and conditions that underlie the observation. It allows designers and evaluators to investigate, evaluate and select solutions closest to the design concepts generated with the goal of improving some attribute and function of the system. For instance, when observing the system at this level, the human perceives the way in which components of the system interaction are organised. The perspective changes as he/she interacts with other components of the system.

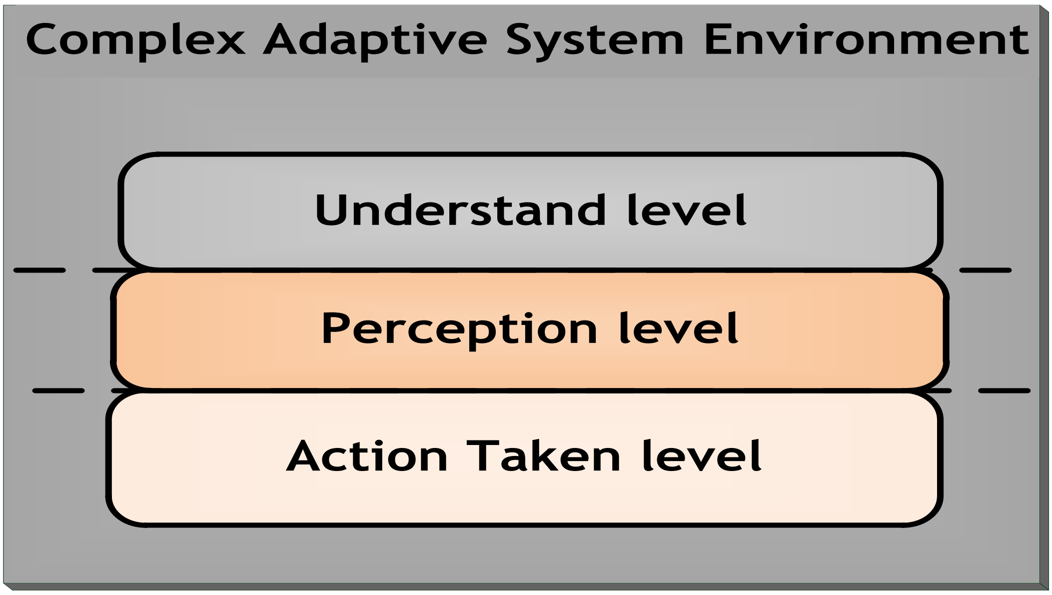

Figure 4-2: Three faces of complex adaptive systems conceptual model (Source: Author)

The third level represents the ‘action’ taken. This then enables the capturing, representing, modeling and codifying of design knowledge and information about design processes, environments and life cycle issues.

On each conceptual level, elements and properties are defined which support the analysis and understanding of Complex Adaptive Systems. Many other complex adaptive system characteristics exist. Table 4-1 shows the three faces of the Complex Adaptive System model. The following collection of CAS characteristics is based on multiple scientific resources on complex systems (Axelrod and Cohen 2000; Cilliers, 1998; 2005; Eoyang and Berkas, 1998; Marion and Uhl-Bien, 2002; Barnes et al., 2003; Rotmans, 2005; Waldrop, 1992; Bagdasaryan, 2008; Ramalingam et al., 2008; Mitchell, 2009; Ryan, 2009).

Table 4-1: Categories and themes relating to the dimension of the three faces of Complex Adaptive System model

Dimension	Characteristics	Definition
	Observable Interaction	Interactions between the system’s components induce systematic interdependencies between them.
	Emergence	Emergence is defined as the information a system or process produces. The properties of a system are

Complexity Theory as it applies to "Understand level"		emergent if they are not present in their components, i.e., global properties which are produced by local interactions are emergent. Emergence is the aggregate system behaviour, which is a result of the behaviour of the individual actions of the agents, the interaction between the agents and input from the environment. Emergence can take place at the level of a phenomenon observed or at the level of the description of the phenomenon observed.
	Butterfly effect	Size of change does not determine size of change. A big issue does not necessarily need big change.
	Nonlinearity	In some cases, small changes might have large effects on a non-linear system, while large ones could have little or no effect.
	Phase Transitions	System behaviour changes suddenly and dramatically (and, often, irreversibly) because a tipping point, or phase transition point, is reached. As the systems of interest are dynamic, undergoing continuous changes that alter the nature of connections and make them unpredictable in their outcome, we can't simply look to the past to predict the future. It is essential therefore that the system observer looks for signals that a system is about to go into a phase transition.
	Self-similarity	Refers to the fact that a complex system often looks the same at different scales. A well put example is given by Mitchell (2009): If you look at a small section of the coastline it does not have exactly the same shape as the entire coastline but is visually similar in many ways.
	Self-organization	Self-organisation has been used to describe systems where the local interactions lead to a global patterns or behavior (Gershenson, 2007). Self-organization of CAS means that they are able to develop a new system structure. It is a result of the system's

		internal constitution and not a result of external management (Rotmans, 2005).The ability of a complex adaptive system to autonomously change its own behaviour and structure in response to events and to environmental changes that affect behaviour.
	Multi-understanding	Multi-understanding means that complex systems may have many different descriptions (Cilliers, 1998). They cannot be reduced to simple definition.
	Openness	The openness of CAS means that they interact with their environment (Rotmans, 2005). It is also difficult to define clearly where complex and adaptive programmes begin and end (Barnes et al., 2003). CAS are also open to external influences.
	Holism	This is a rejection of reductionism. Holism can be summarised by the phrase “the whole is greater than the sum of its parts”.
Complexity Theory as it applies to “Perception level”	*Historical conditions*	A complex adaptive system cannot be understood as a snapshot of the present, without also taking its evolutionary history into account.
	Distributed control	While lack of central control is always a feature of complex adaptive systems, it is not sufficient for complexity since non-complex systems may have no control or order at all.
	Feedback loops	Existence of feedback loops means that the system has a tendency to use its own output to make adjustments in its inputs and processes (Eoyang and Berkas, 1998). Two types of feedback loops can adjust the behaviour of complex adaptive systems: negative and positive. Evaluation process is an example of feedback loop, either positive or negative. It is positive when the system learns from the evaluation and enhances its performance, or negative when negative evaluation results

		discourage program participants.
	Scale	The scale of observation influences what patterns are perceived within a complex adaptive system. The situation cannot be successfully addressed at only one scale and due to the effect of external influences decision-makers cannot afford to focus only on events inside some arbitrary boundary.
	Co-evolution	The ability of a complex adaptive system to autonomously change its behaviour and structure in response to changes in the system environment and, in turn, to cause changes in the environment by its new behaviour.
Complexity Theory as it applies to "Action Taken level "	*Simple Rules*	The emerging patterns may have a rich variety, but the rules governing the function of the system should be made to be quite simple.
	Anticipation	Preparation of the system for changes before they occur; helps the system to adapt without it being perturbed. Solution is always part of the system. It is not external to the system.
	Adaptation	Systems can adapt to inputs and evolve. They must emphasise the ability to adapt to changing environmental conditions. The ability of a complex adaptive system to adjust its behaviour in response to the occurrence of events that affect its operation.
	Coupling and Connectivity	Systems can be loosely coupled or they can be tightly coupled. In the context of complex engineering systems, you can change the characteristics of highly connected 'nodes' which could serve as leverage points for drastically improving the performance of the system.

It should be noted again that these three levels are conceptual distinctions, used for a better understanding of the systems and that they do not exist as such on top of each other. In system analysis, structure is primarily the most important characteristic of a system. The proposed ‘three faces of complex adaptive systems (Understand – Perception – Action Taken) conceptual model is demonstrated through a qualitative phenomenological study informed application to identification and construction of managerial complexity competency model presented in Chapter 8. This thesis argues that, designers and managers can still control/predict some characteristics of system outputs, provided they are designed with an understanding of the causes of complexity.

4.2 Architecting Challenges and Issues

In this section, we report the findings of an empirical investigation of an organization which is progressing towards applying complex adaptive system engineering. It addresses the thesis third research objective. More background details on conducting the Delphi study are provided in Appendix B.

4.2.1 The Delphi Study Results

4.2.1.1 Participant demographics

The Delphi study was conducted with 26 experts as panel members. Table 4-2 summarises their demographics.

Table 4-2: Participant demographics

Group Characteristics	Category	Total
Age	18 - 25	2
	26 - 40	10
	> 40	14
Education Level	Bachelor’s	13
	Master’s	12
	PhD	1
Work Experience (years)	0 - 5	9
	5 – 9	11
	>10	6

4.2.1.2 Distribution and Qualitative Analysis of Round One

In the initial phase of the study, experts were provided with an overview of the design and purpose of the study, an estimate of how much total time they would be expected to contribute to the study, and an open-ended question. Communication primarily was conducted through face to face meeting and electronic mail. Experts were asked to respond to the following the study question:

What challenges and issues are considered important by project managers, system architects and designers of complex systems as having significant impact on systems architecture design?

According to Hsu and Sandford (2007), the type of data analysis researchers use for Delphi studies is at the discretion of the researchers themselves. The qualitative information garnered for this round was analysed and grouped into similar categories. Table 4-3 shows the list of critical systems architecting challenges and issues identified. The identification of the 23 architecting challenges and issues answers the first part of the research objective 3.

Table 4-3: The major Challenges and Issues for Complex Adaptive Systems Architecting as Reported by Systems Architecting Experts

No	Challenges & Issues	SA1	SA2	SA3	SA4
1	Lack of clear mechanism for incorporation of ability to change lifecycle system properties rapidly and easily		✓	✓	
2	Analysis of the requirements uncertainty stemming from the Directive and its relationship to system architecting		✓	✓	
3	Analysis of the requirements uncertainty stemming from consultation papers and relationship to system architecting		✓	✓	
4	Effective coordination strategies for managerial complexity issues	✓	✓	✓	
5	Lack of clear mechanism for incorporation of ability of the risk models to be insensitive to input of wrong data or unexpected large data		✓	✓	✓
6	Assessment of potential system architecture functionality		✓	✓	
7	Lack of well-defined architectural process and development plans for systems in an uncertain		✓	✓	

	environment				
8	Lack of effective decision-making powers and independence of the architectural team	✓		✓	
9	Lack of clarity/understanding of solution space		✓	✓	✓
10	Dialogue and interactions with supervisors	✓		✓	
11	Problems in the cooperation between technical and business people	✓		✓	
12	Adherence to Capability Maturity Model Integration for Development (CMMI-DEV) currently used in the company		✓	✓	✓
13	Team education and effective allocation of team to specific assignments are limited and poorly handled	✓		✓	
14	Adherence to quality framework given by ISO 9126 currently used in the company			✓	
15	Documentation and Communication of design processes		✓	✓	
16	Lack of flexible method evaluating architecture suitability		✓	✓	
17	Lack of appropriate mechanism for applying of value models when choosing envisioned architecture	✓		✓	
18	Lack of effective communication and feedback (between stakeholders)	✓	✓	✓	
19	Lack of clear long-term strategy for Regulatory Governance	✓		✓	
20	Lack of a clear strategy for managing complexity through the lifecycle of the system		✓	✓	✓
21	Information asymmetries and structured management of knowledge			✓	✓
22	Building trust in a multidisciplinary/interdisciplinary team	✓		✓	
23	Lack of sufficient resources	✓		✓	

Based on the identified challenges and issues, a conceptual model was developed forming logical groupings around related challenges and issues. Using a combined process of global analysis (a general way of organizing information about the problem context that surrounds the architecture), purpose and activities of system architecting and the researcher experience as a system architect, we organise our knowledge of the architecting challenges and issues into a conceptual model of four dimensions. This definition parallels Nightingale and Rhodes's conceptualisation of enterprise systems architecting which "involves a relation among four terms: the organization view, the process view, the knowledge view and the enabling information technology view" (Nightingale and Rhodes, 2004).The conceptual model is labeled CIRD conceptual model, shown in Figure 4-3 and we propose it as a competency statement for complex adaptive systems design.

4.2.1.3 CIRD Conceptual Model

The CIRD model suggests that there are four dimensions or characteristics of complex adaptive systems architecting that a system architect or decision-maker must be concerned about: Organization and Governance – (marked column SA1 in Table 4-3), Methodology - (marked column SA2 in Table 4-3), Process and People - (marked column SA3 in Table 4-3), and Data and Systems - (marked column SA4 in Table 4-3). The process of developing and managing complex adaptive systems architecture comprises interactions among the four dimensions. Each of these four dimensions is further subdivided into architectural challenges and issues for a decision-maker to consider.

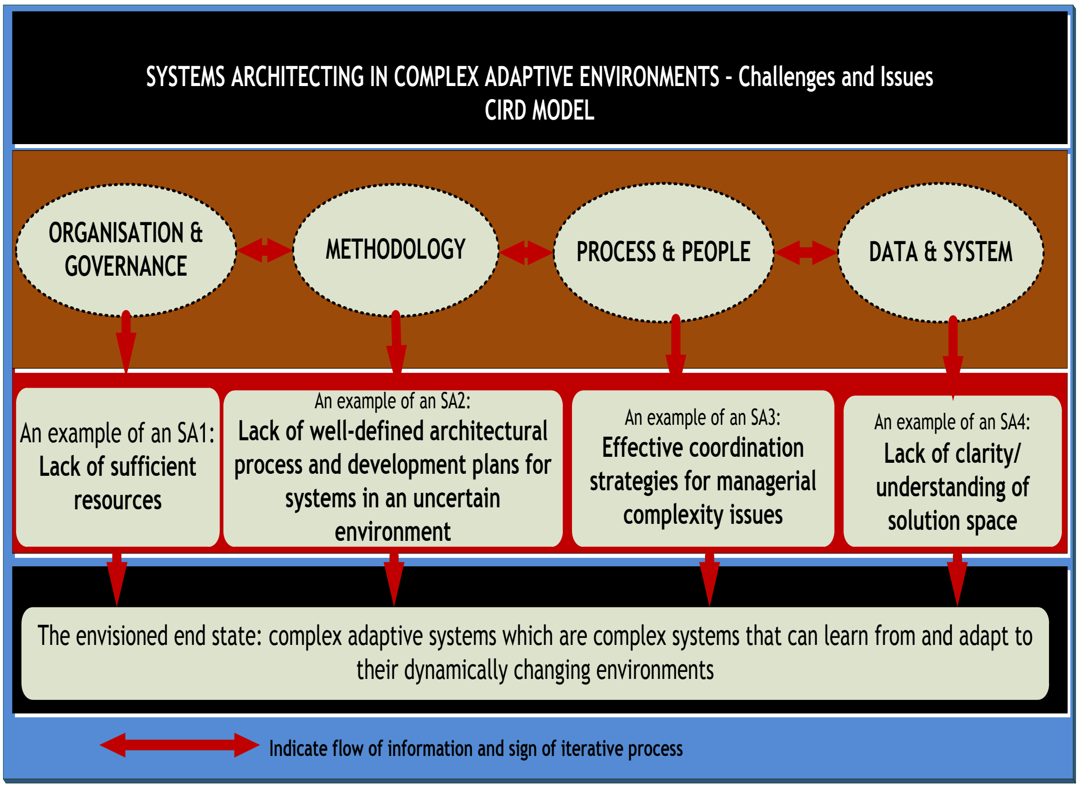

Figure 4-3: Model of complex adaptive systems architecting challenges and issues

By making the CIRD model and definition explicit, we reveal our assumptions about what we think system architecting might be, which is useful for understanding the limitations of any subsequent knowledge being developed in this thesis and future research efforts. In this way our ideas are also open to scrutiny, challenge and, if necessary, modification. This categorisation has been done to increase readability as well as indicate whether a certain category is overrepresented.

The set of connecting links represents the presence of a relation or interaction among these dimensions and related elements. We also made it generic enough that it could be used, in whole or in part, across organizations in every complex adaptive systems solution domain. The dynamics among these four dimensions determine the perceived success of the system. The following sub-sections of the thesis discuss selected challenges and issues identified under appropriate categories of the CIRD model.

Organization and Governance-related challenges and issues

The "Organization and Governance" cluster is related to adaptive management support and governance including accountability and decision processes in the context of large systems architecting initiatives.

The participants of the Delphi study highlighted many challenges and issues relating to the "Organization and Governance" cluster labeled SA1 in Table 4-3. According to the perceptions of the participants, absence of active "Organization and Governance" is seen through, for instance, No8 - 'Lack of effective decision-making powers and independence of the architectural team', No13 - 'Team Education, Experience and Effective team building/motivation are limited and poorly handled' and No18 - 'Effective communication and feedback (between stakeholders)' architectural challenges and issues.

The reported challenge and issue No 13 above was considered important by participants and is an asset when conducting the systems architecting processes. Thus, this particular challenge and issue has implications for development practice, education and training.

Methodology-related challenges and issues

The challenges and issues considered to be 'Methodology' related are concerned with the technical actions throughout the life cycle. We mapped the following challenges and issues named ‘SA2’ in Table 4-3 to this category. They include No4 - ‘Effective coordination strategies for managerial complexity issues’, No7 - ‘Lack of well-defined architectural process and development plans for systems in an uncertain environment’ and No1 - ‘Lack of clear mechanism for incorporation of ability to change lifecycle system properties rapidly and easily’, respectively. The selected challenges and issues can show the absence of clear and documented processes for how the system and software architecture is developed. This could be because it is hard for management to see any real benefits from structured architectural work. It also shows a lack of clear strategy for how architecture should be evolved in the future.

Absence of clear strategy for architecture complexity management will most likely result in solutions that may not appear satisfactory as conditions change. The reported challenges and issues (No4) as perceived by the participants is probably an acceptance that complexity in the architecting organization, as well as the envisioned system, has increased, leading to a situation where existing processes are insufficient.

Process and People-related challenges and issues

The challenges and issues considered to be ‘Process and People’ related are concerned with the technical actions throughout the life cycle. We have mapped the following challenges and issues named ‘SA3’ in Table 4-3 to this category. Challenges and issues No22 - ‘Building trust in a multidisciplinary/interdisciplinary team’ and No9-‘Lack of clarity/understanding of solution space’, No13 - ‘Team education and effective allocation of team to specific assignments are limited and poorly handled’ and No21 - ‘Information asymmetries and structured management of knowledge’ from the perspective of the research objectives presented in this thesis is probably a sign of the need of enhancing the anticipatory capacity of the architecting team through new competencies.

Processes are supposed to execute project plans, assess actual achievements and progress with reference to the initial plans but where the architecting team does not have a good understanding of the processes available is a sign of the need for a new simplified process or competency enhancement requirement. Another important architectural challenge revolves around the representation of knowledge (No21 in Table 4-3), showing the research needs for representational formalism in complex adaptive system architecting.

Data and Systems-related challenges and issues

The challenges and issues considered to be ‘Data and Systems’ related are concerned mainly with the technical actions throughout the life cycle. We have mapped the following challenges and issues named ‘SA4’ in Table 4-3 to this category. Challenges and issues No12 ‘Adherence to Capability Maturity Model Integration for Development (CMMI-DEV) currently used in the company’ and No5 ‘Lack of clear mechanism for incorporation of ability of the risk models to be insensitive to input of wrong data or unexpected large data’ are examples of clear manifestation of the fact that decisions made at the conceptual architecting level have implications even at the maintenance stage. ‘Lack of clear mechanism for incorporation of ability of the risk models to be insensitive to input of wrong data or unexpected large data’ indicates that uncertainties can be both external and internal and manifestations, noticeable after the system has gone into production. Therefore, anticipating the various sources of uncertainties and preparing the system to be easier to change is a necessary requirement in the architecting process.

4.2.1.4 Weighting of the identified Architecting Challenges and Issues

Rounds Two and Three. As explained in the description of a typical Delphi study, responses to the first round of open-ended questions were analysed and categorised into Likert-scaled questions focused on understanding what challenges and issues are the most and least important. Experts were asked to revise or clarify their comments from Round One, as well as provide importance ratings on the Likert-scaled questions.

When responses to the second round were received, the group mean for each question were calculated. For Round Three, each expert received an individualised version with the same questions as Round Two, but also the results of the group mean for each question, as well as their previous ratings for each question. This allowed each participant to view the average group response to each challenge and issue, and compare their individual ratings with the group as a whole.

The Delphi Round 3 resulted in assigning different levels of importance to the identified challenges and issues as perceived by the participants. Table 4-4 indicates how each of the challenges and issues is perceived (i.e. from ‘very important’ to ‘neither important nor unimportant’).

Table 4-4: The Major Challenges and Issues for Systems Architecting - How important it is?

Systems Architecting Challenges & Issues		
No	**Very important (1.00 to 1.49)**	
1	Lack of clear mechanism for incorporation of ability to change lifecycle system properties rapidly and easily	1.25
5	Lack of clear mechanism for incorporation of ability of the risk models to be insensitive to input of wrong data or unexpected large data	1.36
7	Lack of well-defined architectural process and development plans for systems in an uncertain environment	1.36
2	Analysis of the requirements uncertainty stemming from the Directive and its relationship to systems architecting	1.43
13	Team education and effective allocation of team to specific assignments are limited and poorly handled	1.45
20	Lack of a clear strategy for managing complexity through the lifecycle of the system	1.46
	Quite Important (1.50 to 1.99)	
12	Adherence to Capability Maturity Model Integration for Development (CMMI-DEV) currently used in the company	1.86
3	Analysis of the requirements uncertainty stemming from Consultation papers and relationship to systems architecting	1.88
14	Adherence to quality framework given by ISO 9126 currently used in the company	1.88
16	Lack of flexible method evaluating architecture suitability	1.88
8	Lack of effective decision-making powers and independence of the architectural team	1.92
6	Assessment of potential system architecture functionality	1.96
	Somewhat Important (2.00 to 2.49)	
21	Information asymmetries and Structured Management of Knowledge	2.04
18	Lack of effective communication and feedback (between stakeholders)	2.04

19	Lack of clear long-term strategy for Regulatory Governance	2.04
15	Documentation and Communication of design processes	2.04
17	Lack of appropriate mechanism for applying of value models when choosing envisioned architecture	2.05
4	Effective coordination strategies for managerial complexity issues	2.08
10	Dialogue and interactions with supervisors	2.08
11	Problems in the cooperation between technical and business people	2.17
22	Building trust in a multidisciplinary/interdisciplinary team	2.29
23	Lack of sufficient resources	2.38
Neither Important nor Unimportant (2.50 to 3.00)		
9	Lack of clarity/understanding of solution space	2.54
Scale: 1.00 – 1.49 = very important, 1.50 – 1.99 = quite important, 2.00 – 2.49 = somewhat important, and 2.50 – 3.00 = neither important nor unimportant.		

Selected conclusions from Table 4-4 include:

1. From the participants' perspective, the most important architectural challenge and issue facing them is No1 and mitigation of it will lead to a more successful system architecture development. From Table 4-4, we can conclude that No1 has a higher significance to the success of their particular project than Nos.5, 7, 2, 13, and 20.
2. Challenges and Issues No12 has a higher significance than Nos.3, 6, 8, 14 and 16.
3. Challenges and Issues No4 has a lesser significance than Nos. 15, 18, 19 and 21 but more important than Nos. 9, 10, 11, 22, and 23.

The simple purpose of assigning weightings to the identified challenges and issues is to help the participants establish work priorities in terms of their proposed conceptual design framework and for the researcher to define possible areas for further research. For the purpose of the current research in this thesis, the researcher deliberately selected two of the identified challenges and issues for further discussion. The selected architectural challenges and issues are Nos.4 and7. These two are more closely related to the research objectives defined for this thesis. Although Nos. 1 and 5 were perceived by the Delphi study participants to be more important than the selected No. 7, the researcher judged both challenges and issues can be architecturally dependent on No. 7. The two selected challenges and issues both reflect the focus of this thesis.

4.2.1.5 Mitigations for selected Challenges and Issues

Round Four. In the final round of the study, experts were provided with an overview of selected architectural challenges and issues and were asked to respond to the following the question:

What techniques and strategies do you think are most effective to facilitate solution to the challenges identified?

In these paragraphs, we discuss two of the selected challenges and issues further based on what practitioners perceive as mitigations. The selected challenges and issues are as follows:

- Effective coordination strategies for managerial complexity issues
- Lack of well-defined architectural process and development plans for systemsin an uncertain environment

Effective coordination strategies for managerial complexity issues

An effective coordination strategy for managerial complexity in architecting design practice was reported as a major challenge and issue by the participants. The principal question the participants of this Delphi study were seeking answers to was what kinds of strategies enable effective co-ordination in complex and uncertain organizational programs? Mitigation suggestions, as perceived by participants, can be viewed from (‘Methodology’ and ‘Process, Service and People’) related challenges and issues. Possible mitigations include:

Recommendation 1: To investigate the possibility of creating a model that can aid decision-making when choosing a system development process integration strategy.

Recommendation 2: To investigate the possibility of creating a process more amenable to project management and control, thus minimising risk and uncertainty and which can aid project manager’s decision-making.

Recommendation 3: Developing more training/learning opportunities for all those working in complex adaptive systems design programs and not necessarily for only those with management responsibility.

Recommendation 4: Collaborating is a great way to spark new ideas and creative inspiration comes from external sources. Thus any architecting process that encourages solution space for collaboration is positive according to the study participants.

Lack of well-defined architectural process and development plans for systems in an uncertain environment

There is what can be called a general consensus among Delphi study participants that the main cause of this challenge and issue is that too little effort and time is spent on defining such an architectural process. Not spending enough time is believed to be caused by the missing architectural methodological approach, which unavoidably results in an unfocused and un-prioritised effort. In recent years, most modern system developments have been faced with a large increase in system complexity as well as in the complexity of the development team. According to the participants in the study, this challenge and issue is near the top of challenges and issues that need to be resolved. Mitigations and recommendations resulting from the Delphi Round 4 as judged by the participants include:

Recommendation 1: To overcome the problem of inadequate architecture development process, participants agreed on the need for systems architecting to be managed as a program, with clear leadership, since the processes themselves are complex, having strong interdependencies and therefore cannot be considered in isolation. Since complex adaptive systems architecting requires consideration of the environment in which the system will be designed and operate as well as the engineering organization building the system even at the conceptual design phase, having a proper design methodological approach in place means there are defined roles and responsibilities for architectural matters.

Recommendation 2: What is needed to help the cost-effectiveness of system development and reduced development schedule is a kind of reference architecture designed for changeability. This is a particular mitigation or recommendation argued for by both the program manager and the enterprise architect.

Recommendation 3: A recurring opinion among participants is the need for an architecting process and architecture that enhances communication between its developers and the engineers responsible for system specification and operation; an architecture that explains, not just what gets built, but why it gets built the way it does.

4.3 Chapter Summary

The first central objective in this chapter was to explore the properties of complex adaptive systems and the way these contribute to the understanding of a typical system. To answer this question, a conceptual model was proposed based on Complex Adaptive Systems. The conceptual model consists of three levels (understand, perception and action taken) and each level contains several properties. This makes a system adaptive complex. It is proposed that the use of the model, the complexity of complex adaptive system can be explained and understood. The second central objective addressed in this chapter was what are the challenges and issues facing a complex adaptive system design or engineering organization. To answer this question, an exploratory Delphi study was undertaken. The first outcome of the Delphi study was a discovery of 23 important architecting challenges and issues that complex adaptive system architecting decision-makers must consider and be aware of when planning and executing systems architectural projects.

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CHAPTER 5 CXLUD FRAMEWORK DEVELOPMENT

This chapter addresses the fourth of the seven research objectives introduced in Section 1.3. Bringing together the influences of the previous chapters, this chapter begins to develop a framework that addresses the first of the two research questions. In this chapter, the Complex Systems Lifecycle Understanding and Design (CXLUD) Framework – a conceptual design methodology is discussed, while addressing the first research question posed in Section 1.3. The approach packages a low-cost but effective design method and processes that can stimulate creativity and enable engineering of complex adaptive systems (architecture) in a heterogeneous, uncertain and changing context for specific design problems. A key aspect of effectiveness is the frequency and quality of interaction between the different aspects of a design process.

The CXLUD development builds on the widely held view in the complex systems design community that the starting point on having innovative, systemic and repeatable processes is having a design environment from within which innovation can take place. Different approaches are integrated together, which enables the proposed approach to satisfy desired properties. The proposed CXLUD Framework, as with most design methodologies, does not provide ready-made solutions to problems. What it does is provide a conceptual framework and a language, to assist the continuous evolving of the solution to the problems. Its main purpose is to aid intuition rather than prove theorems or seek patterns in data.

The remainder of this chapter is organised into three sections. In Section 5.1, concepts necessary for understanding and implementing the CXLUD stages are introduced. The CXLUD Framework is presented in Section 5.2, followed by Discussion and Conclusions in Section 5.3. Figure 5-1 shows how this Chapter fits into the overall research process, where the arrows mean “lead to.”

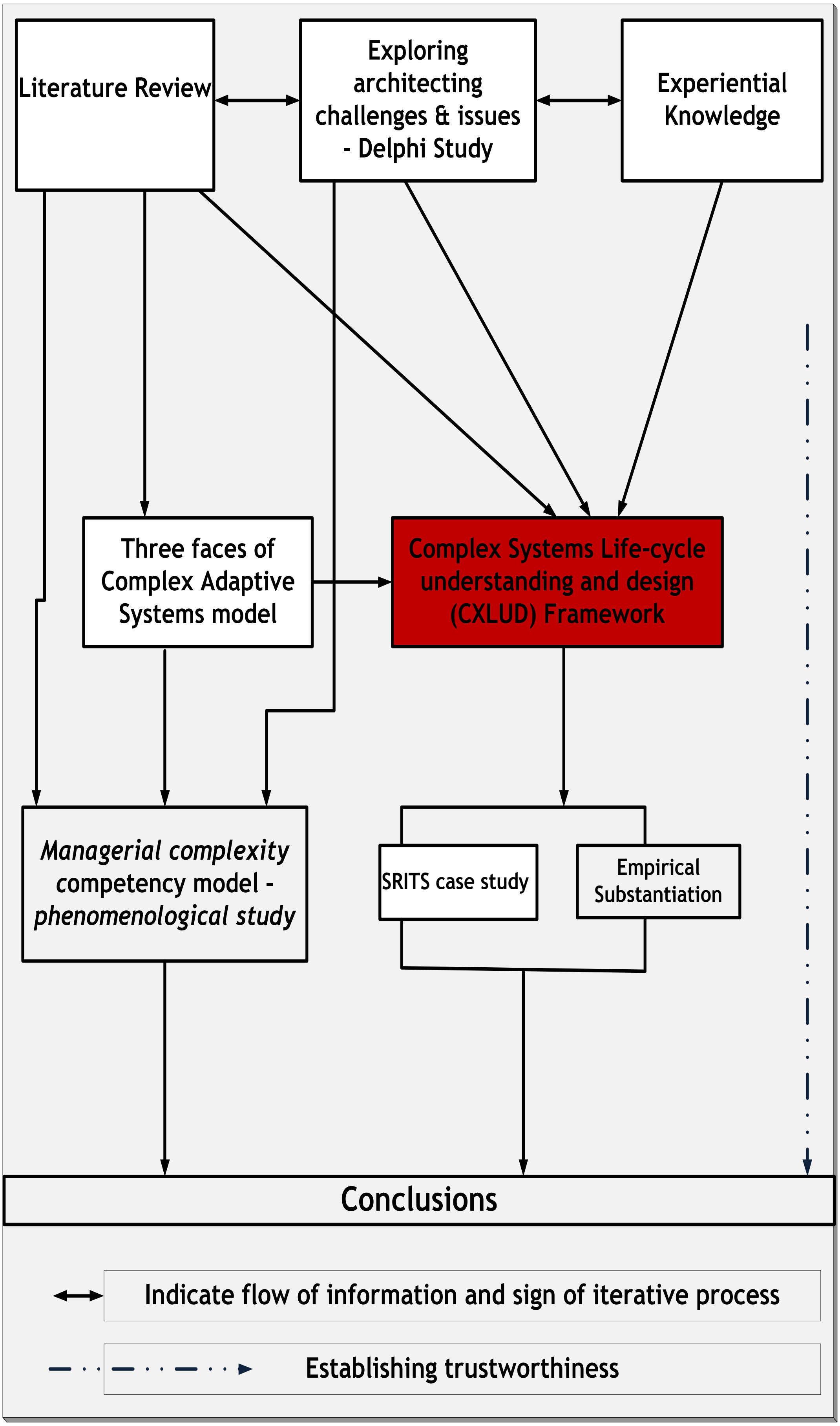

Figure 5-1: Research process with current stage highlighted

5.1 Creative Anticipation

The concept of “Creative Anticipation” (CA) is proposed as a label in this thesis representing design concept generation and ideation procedures with anticipatory treatment. It is informed by literature and experience gained from system development in industry. It involves a set of explicit lectures and prompt questioning which encourages participants to generate design ideas or make decisions. Diverse ideas can be generated through repeated application of different CA sessions. It is a simple, affordable and intuitive procedure to help complex system designers generate strategies early in the systems design. The proposed CA can be said to revolve around mimicry of the processes that promote rapid innovation through competition in that different teams could be set up to compete in generating solutions in different CA sessions. In that sense, CA contributes to the challenge of creating a system design environment in which continuous innovation can occur and this can be argued to transcend readiness potential. CA exploits value-focused thinking and decisional value paradigms in its process. The aim is to provide a practical approach leading designers to rapid lifecycle value improvements by explicit considerations of different means to value robustness.

To implement CA successfully as a design procedure approach, it is assumed that the more design information made available, the better is the decision making. The theory process is based on the value focused thinking concept (see Section 2.3.8). In practice, when confronted with a difficult decision; a decision maker perceives their options through a decisional value lens, that is, from an envisioned experience rather than an actual one.

As shown in Figure 5-2, CA involves the following steps.

1. Step 1 is the envisioned design problem description. The process starts from a preliminary literature review in form of external knowledge or a priori solution knowledge. The purpose of the review is to gather existing information on the system design or architecting problem of interest and inform better explicit lecture and prompt questioning (Step 2).

2. Step 2 is the explicit lecture and prompts questioning; here, the design problem is described through an explicit lecture including any clarifying information deemed useful to the participants. The explicit lecture and prompt questioning simulate creativity via questions of: ‘why’, ‘what’ and ‘how’. The duration or the scope of the “explicit lecture” must be limited to enable focus on the essentials. Every explicit

lecture has a purpose, something the design and architecting team wants to learn or explore.

3. Step 3 is use case/data collection - generated concepts from step 2 are implemented in the form of data collection as ‘use cases’ or any other analysis/communication model. The forward and backward facing arrows simply indicate, for instance, that after the initial capture of ‘use case’, the design problem description can be refined if more details are needed. A simple Excel spreadsheet prepared with proper sections can be used for the collection of data and enables participants to type in real-time creative ideas to the design problem of interest. The anticipated scenario was for a moderator of the CA session to initiate an ideation topic and each member of the session to write an idea addressing this topic. Each written idea will be displayed to all the team members to stimulate creativity. Every member can reply, comment and append new ideas to any idea in the thread just like is obtainable in networked chatting software. However, this was not the case in the current research and it is outside the scope of this thesis. For this thesis, data was manually collated and analysed.

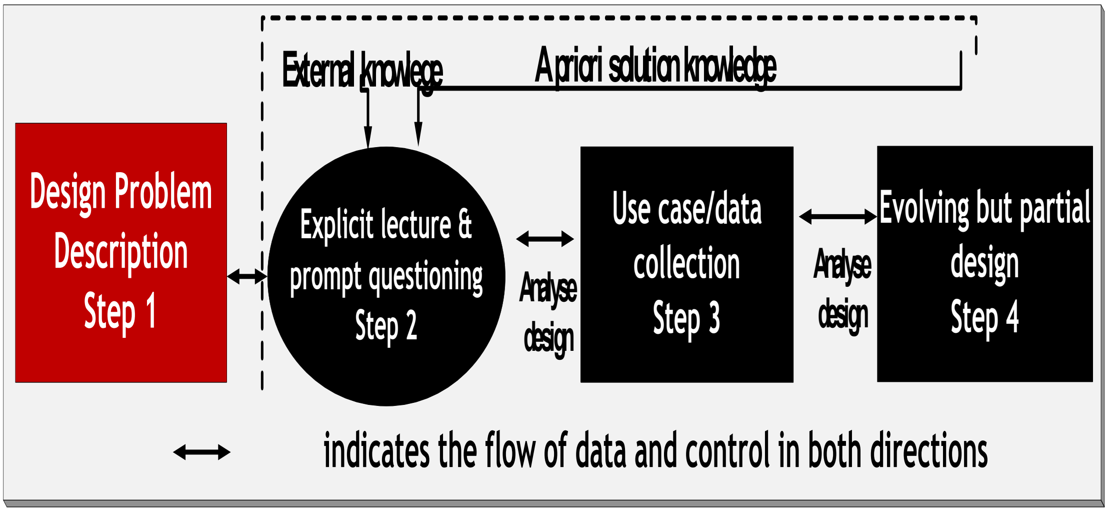

Figure 5-2: Schema for the proposed Creative Anticipation Design Procedure (Source: Author)

4. Step 4 is evolving but partial design and consists of analyzing in more detail the collected data produced at the end of the session. Similarly, if the generated design concepts are evaluated negatively, the whole process can be repeated until acceptable design concepts are generated. The results of the analysis are presented in the form of morphological chart or function-means tree (adapted from Dym and Little, 2000). A morphological chart is a tool that represents possible solutions to a design problem. It consists of a list of the decomposed sub-functions (where applicable) of a design and the means by which each sub-function may be realised.

Another message behind Figure 5-2 is that an *a priori* system solution (such as heuristics developed through experience) can be combined with external (new) information to create the explicit lecture and prompt the questioning session. A set number of three iteration analysis rounds are used as a convergence criterion for the CA sessions. The criteria were selected to adapt to the time available and the availability of participants. The motivation for using the proposed CA as a design abstraction for design concept generation solutions comes from the characteristics of both evolutionary development and adaptation in complex adaptive system. As highlighted in Figure 5-3, all stages of the CXLUD Framework can potentially be driven by the CA procedural steps highlighted in Figure 5-2. A CA is a creative approach. Using a creative approach also implies that we are attempting to advance toward an outcome that is unstructured and open-ended.

5.2 Overview of the CXLUD Framework

In this section, the concept of a CXLUD Framework – a conceptual design methodology is introduced. CXLUD is built upon research reported in literature (e.g. see Section 2.3.8) and empirical results collected from experts in academia and industry (e.g. as presented in Section 4.2). Bringing together the influence of the heuristic principles, as well as the inputs from decision making theory, we developed a conceptual design framework which considers three major stages, as shown in Figure 5-3, integrated with the CA for progressing through the stages. The three stages are: Design Innovation Control, System Life Cycle Control and Architecture Realization Control. The first stage, Design Innovation Control, is the process of identifying the need and potential for a system implementation. The second stage, System Life Cycle Control, relates to finding and agreeing upon appropriate system characteristics to support problem definition documented in Design Innovation Control. The third stage, Architecture Realization Control is a means of specifying implementation and the system control mechanism. The decision point in the framework labeled ‘Decision Point: Execute Change?’ is incorporated to manage a mechanism to execute a change after experiencing a perturbation based on the information feedback from the operational system.

CXLUD is referred to as a framework to reflect its ability to provide a structure in which the needs of the affected stakeholders are identified, alternative concepts are generated and can be evaluated and one or more concepts are selected for further development and testing. CXLUD is thus a framework for considering design for value robustness - the purpose of system development is to deliver value. The delivery of value in CXLUD is in terms of the concept selected. The concept generation procedure is critical to ensure proper matching of value delivery to expectation. Note that CXLUD was first introduced in (Amaechi and Counsell, 2012b).

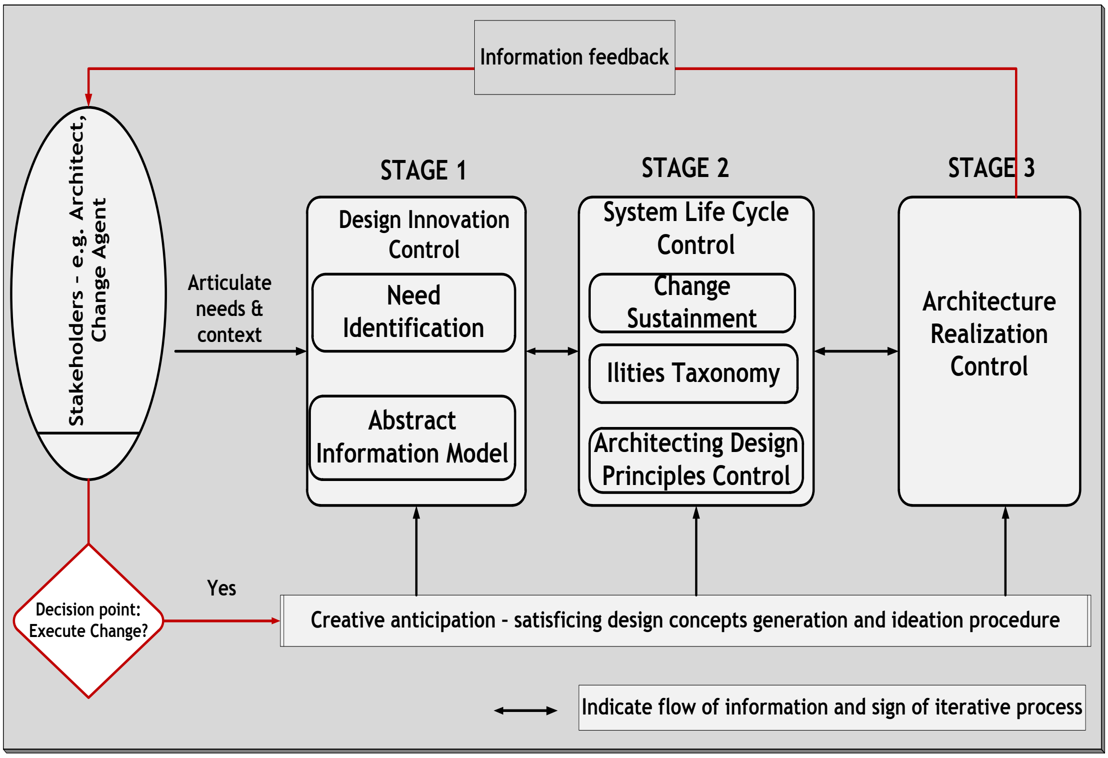

Figure 5-3: Schema for the proposed CXLUD Framework

As seen in Figure 5-3 in the CXLUD Framework the architect is the user of the framework and at the core of the framework is the creative anticipation. The architect (i.e., stakeholders) has both articulated and unarticulated value/goals – i.e., their perceived importance of the system design outputs, may change based on new information provided. In other words, in order to deliver value, a system design goal must be perceived by a decision maker (e.g., an architect) and be delivered by the system (design). Any change in the stakeholder perception of the value delivered will lead to a proposal to system (design) changes. CA enables an in-depth exploration of each step in the stages. With Creative Anticipation, the CXLUD framework is able to provide an environment in which continuous innovation can occur. Overall, the three CXLUD stages occur in sequence, but some feedback can occur between them. The primary purpose of the feedback is to refine the system concepts, various contexts, value propositions and assumptions under evaluation.

Since information is constantly being created at every stage, it is necessary for the designer and decision maker to be aware of the need to continually update the balance of information. Interaction with and feedback from the framework users at each stage provide one mechanism for learning from the system design process. The inter-dependency of the stages is exemplified by two relations: ‘specification’ is implemented by ‘implementation’ and ‘implementation’ needs ‘specification’ (Figure 5-4). Thus, we see that recurrence is an inherent feature. Knowledge gained from the System Life Cycle Control for instance flows back to the Design Innovation Control to improve the fidelity of the specification and design concepts selection.

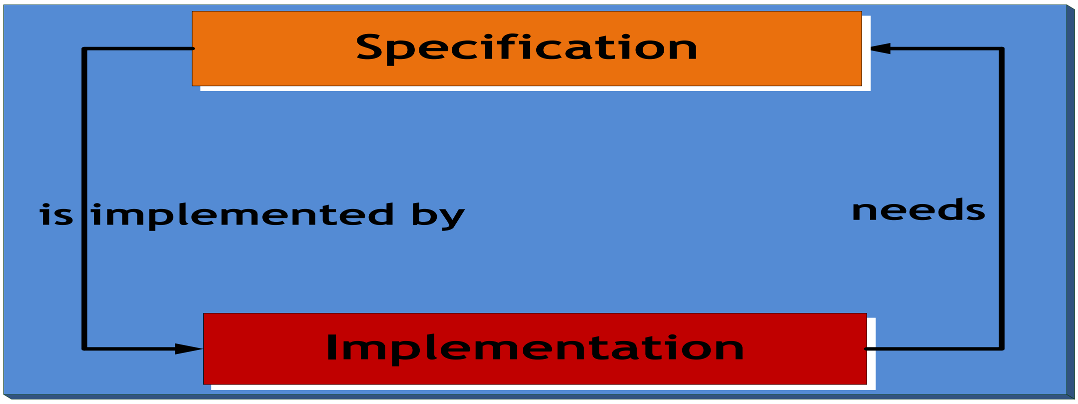

Figure 5-4: The relations between CXLUD three Stages (Source: Author)

We considered these stages and steps as sufficient because they incorporate all the inputs required in conceptual design. The order is also relevant, because each stage and step provides inputs for the next one. The model also acknowledges the importance of having an iterative process. The CXLUD cycle begins with available knowledge (i.e., from the enterprise design team) and ends with increased available knowledge (i.e., with architectural realization control). The stages in the framework are described in the following sections.

5.3 Details of the CXLUD framework

The details of each stage in the framework are presented here.

5.3.1 Stage 1 - Design Innovation Control

The goal of the *Design Innovation Control* phase is to fully understand the system as it currently exists, documentation of known problems, as well as articulating the relevant problems and desired future goals for the system. Thus, it has the purpose of acting as an agreement between the system owner and the system architect/designer. The *Design Innovation Control* phase motivates the entire project lifecycle. It achieves its goals following three iterative steps, described below.

5.3.1.1 Step 1 - Need Identification

The *Need Identification* is the construct defined to facilitate the beginning of CXLUD framework analysis process. The key artifact to create at this step is the definition of the overall driving question, problem and specific objectives to be addressed by the system design. The scope of the problem should be explicitly stated, as this will provide the foundation for the problem-solving endeavour and will be used as a basis for design and process decision-making.

5.3.1.2 Step 2 - Abstract Information Model

The purpose of any system is to provide some level of value to the stakeholders of that system. The concept of Abstract Information Model is used here as a construct to facilitate the identification of stakeholders representing those individuals, groups, entities which derive value from association with the system, context in which the decision makers and potential system reside and constraints that will shape the solutions created by the design effort respectively. Stakeholders of a typical complex adaptive system can be defined as the sum of the people, institutions and resources arranged together (in accordance with relevant policies) to maintain and improve the desired values delivered by the system. This means that the customer can be both internal and external. Even at the conceptual design stage, it is essential that all stakeholders are considered because they may have competing value propositions. In practice, every system has what can be called the decision maker, who wields the power over whether a system is created or not. In addition, a rational, value-maximising decision maker would seek to make stakeholder values a subset of their own value. The designer using CXLUD should thus focus on maximising value to the decision maker, who by definition passes through to the designer the needs of the stakeholder set.

The context of a system is technically everything outside of a system’s boundary. The context includes the operating environment, as well as the origin of inputs and the destination of outputs. Potential contexts to define include the external regulatory, political, economic, industry, market, technology and societal environment in which the system operates and competes. Other contexts could include strategic imperatives, ideology and core values of the enterprise creating, transforming or managing the complex adaptive system.

5.3.2 Stage 2 - System Lifecycle Control

The second stage – System Lifecycle Control of the CXLUD framework is a construct to integrate research in shifts (i.e., changing contexts, needs or an involuntary change to the design space) relating to value robustness. As complex adaptive systems progress through changing contexts and needs, their performance may exceed or dip below stakeholder expected values. A complex adaptive system can change; it can remain robust; or may be versatile to meet stakeholder expectations in response to changing contexts and needs. Therefore, the three strategies that systems designers may use to achieve value robustness would be those that facilitate changeability, robustness and/or versatility. The focus in this thesis is on changeability – i.e., focuses on systems that intentionally change.

To facilitate the value robustness design, the System Lifecycle Control stage consists of three steps namely: Change Sustainment, Ilities Taxonomy and Architecting Design Principles Control. The System Lifecycle Control stage has the purpose of delivering a conceptual design solution determined to be capable of dealing with the design problems identified in the Design Innovation Control stage.

5.3.2.1 Step 1–Change Sustainment

Architecting or designing for value robustness comes with the potential to change in order to address changing needs and contexts. The concept of Change sustainment is used here as a construct to integrate research in change agent – change mechanism – change effect relating to value robustness. A typical change agent – change mechanism – change effect construct is represented in Figure 5-5. A change is represented by a path from CAS Design State 1 (CAS A1) to CAS Design State 2 (CAS A2). Figure 5-5 shows the difference between those with internal change agents represented by adaptable changes and those with external change agents represented by an active value robustness enabler (e.g., evolvable or flexile) change. The change agent as defined above is the force instigator for the change to occur. Change agents can either be people or software. The change agents may use various mechanisms to achieve new states (i.e., CAS A2, CAS B1 or CAS C1) with varying costs for change. The location (i.e., internal or external to the system) of the change agent determines the change strategies. Thus, this distinction relies on a definition of the system boundary.

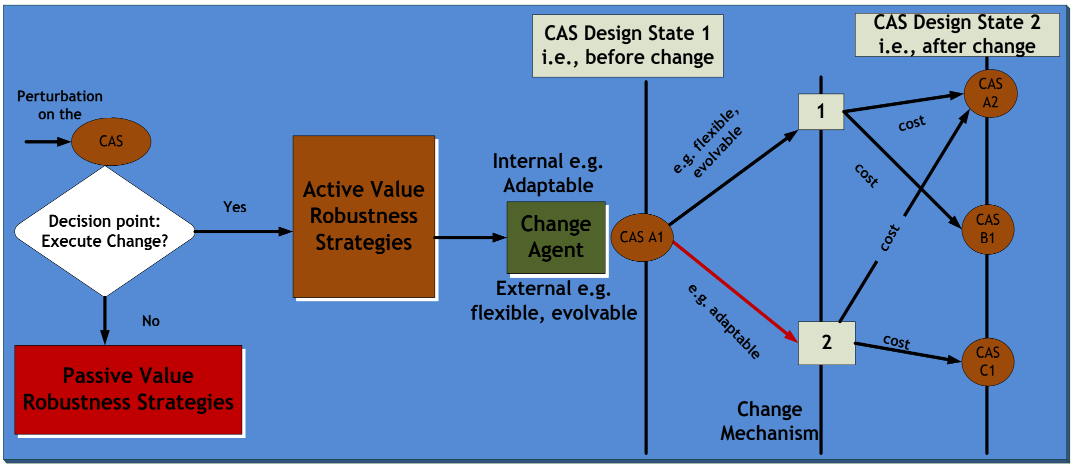

Figure 5-5: Change Sustainment - change agent – change mechanism – change effect construct

The effect of the change is the difference in system states before and after a change has taken place (illustrated in Figure 5-5 as ‘CAS A2 – CAS A1,’ ‘CAS B1 – CAS A1’ and ‘CAS C1 – CAS A1’). In this thesis, how well the greater system operates is the ease with which the initial design can change its architecture. To evaluate the goodness of candidate metrics for Change Sustainment requires a set of criteria. In this thesis, we present this set of criteria as an inquiry tool informed by Christian’s criteria (Christian, 2004). The tool is a list of ‘prompting questions’ which help a decision maker to express their perceived metric and for the designer to understand the expressed change strategies (see Appendix A – labeled Value Robustness Metric Criteria).

The outcome of the inquiry tool is taken as logic statements and serves to determine when a particular design change will occur, how it will occur (i.e., which change mechanism) and to what the original design will change to. Therefore, determining and applying the logic statements has two main concurrent purposes: identify value robust designs and motivate acceptable design principles for value robustness.

5.3.2.2 Step 2 - Ilities Taxonomy

In this step, the desired system characteristics have to be defined. This involves specifying in what way the system implementation should meet the specified system needs and identified desired future goals. The choices made should maintain the systems integrity or prepare the system for changes before these occur in a changing and unexpected environment. An effective system design (architecture) provides a value proposition that is aligned with its envisioned future state and meets the future needs of its stakeholders. The core of Ility Taxonomy concept is that the decision of whether or not to include a particular ility is a function of the nature of the uncertainty that the system faces as well as the change sustainment strategy that the system designer plans to pursue. This in effect reduces the possibility of ‘recency effect.’ A recency effect is a situation where system designers pay too much attention to recent experiences in project selection of possible ilities which may not necessarily generate the best system in future environments.

Three traceable processes are involved in creating the required Ilities Taxonomy. First, ilities are selected based on the consideration of the envisioned future state of the system and consideration of the stakeholder’s future values. Secondly, selected ilities are prioritized based on consideration of stakeholder’s articulated salience and importance. A particular method considered in this thesis for ility selection is a process of mapping future strategic competencies and value of the complex adaptive system into ilities. For example a complex adaptive system strategic competency of ‘responsiveness to market trends’ can be mapped to such ilities as ‘evolvability,’ ‘agility,’ ‘adaptability,’ ‘manageability,’ etc. A stakeholder’s envisioned complex adaptive system value of ‘continuous growth’ can be mapped into ‘evolvability,’ ‘scalability,’ etc. To enable a better dialogue between decision-makers, these system characteristics are better documented in the form of a value hierarchy. A value hierarchy in this thesis represents a pictorial representation of a value structure consisting of the fundamental objective, the values and the measures. Value hierarchies are useful for categorising information in order to share knowledge with others. Thus, the purpose of the Ilities Taxonomy design step is to capture “ilities” capable of coping with the design problem defined in the Design Innovation Control stage in an analytic frame. The Ilities Taxonomy descriptions include suggestions for when to design for each, and this gives the system designer and decision maker(s) an enhanced basis for differentiating between design alternatives.

5.3.2.3 Step 3 - Architecting Design Principles Control

The next step in the System Lifecycle Control is the Architecting Design Principles Control. As the Ilities Taxonomy specified the value adding characteristics of the desired system, Architecting Design Principles Control has the purpose of documenting a set of principles to guide system (architecture) design. The implication for the CXLUD and users is an improved ability to articulate, understand and specify architectural principles necessary for the Ilities Taxonomy specified characteristics. The assumption is that a principles based approach, consisting of a relatively small set of strategic outcome oriented concepts, could serve to guide the application of value robustness characteristics into systems architecture conceptual design.

5.3.3 Stage 3 - Architectural Realization Control

The Architectural Realization Control is the design space exploration stage. This phase requires modeling explicitly the design concepts generated in Stage 2 - explicit consideration of how a system can be created to display the attributes desired. Architecture Realization Control is envisioned as the fast changing interface between the problem and solution spaces. At this stage, the designer can consider possible mechanisms that would allow one instantiation of the design variable set to change into another.In that regard, the mechanisms ensure that the system does what it is required to do. For example, homeostasis as a control mechanism is based on information exchanges between the system and the outer environment and allows the system to maintain a state of equilibrium over time. In other words, a sense of a value robust system is assured with a homeostasis control mechanism.

5.4 Chapter Summary

Decisions early in the system design process, especially in the conceptual design phase, require careful consideration as they will ultimately enable or limit the success of the system. A system can be designed either to robustly perform across a period of fixed contexts and expectations or be designed to change in response to changing needs and contexts in order to retain useful functionality and avoid suffering deficiencies or systemic failure. The CXLUD Framework represents a design environment in which a process of innovation and creative change can take place facilitated by the structured, iterative and non-anonymous CA system design concept generation and elicitation approach. The CXLUD design process takes place in an evolving space of possible and actual designs for the system. This space may be large, complex, and difficult to observe, posing a challenge to understanding the interrelated choices available to designers and decision makers.

The overall constructs defined for CXLUD framework is repeated here for convenience.

1. Design concept generation and ideation mechanism. This construct is called creative anticipation (CA) as described in Section 5.1. It is designed to stimulate creativity and continuous innovation in a complex adaptive system conceptual design

environment. The CA is expected to drive critical research and bring together in an integrated manner the system design team.

2. Analysing the main design problem or mission statement in designing new systems, or making modifications to existing systems in the context of the stakeholder value. This is labeled *Need identification* and it is described in Section 5.3.1.1.
3. Facilitating the identifications of stakeholders representing those individuals, groups, entities which derive value from association with the system, context in which the decision makers and potential system reside and constraints that will shape the solutions created by the design effort respectively. The construct is called The *Abstract Information Model* and is described in Section 5.3.1.2.
4. Integrating change agent – change mechanism – change effect relating to value robustness. This is labeled *Change Sustainment.*
5. Value robustness enabling ilities capable of coping with the design problem and the change sustainment documented in form of a value hierarchy. This construct is labeled *Ilities Taxonomy.*
6. The next construct, *Architecting Design Principles Control*, has the purpose of documenting a set of principles to guide system (architecture) design.
7. Section 5.3.3 describes the final stage of the CXLUD Framework. It is labeled *Architecture Realization Control*. The technical solution as expressed in the Architecture Realization Control supports the designer to achieve his objectives and support the system in the operation.

The CXLUD is intended to be a step-by-step process that a systems architect and/or designer can follow when faced with the early design phase for a complex adaptive system and with the task of bringing complex adaptive systems characteristics such as adaptability, evolvability into the systems conceptual design. That is not to imply a reductionistic assessment of the sub-system, because it still contains emergent characteristics. The framework facilitates qualitative analysis when studying complex adaptive system design decision-making in a particular context. It may also be supportive in a quantitative research setting, for example, structuring the research design. However, in this research project, it has only been used in a qualitative research setting. Thus, we can only claim usefulness for qualitative analysis.

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CHAPTER 6 SRITS CASE STUDY

Chapter 5 introduced the CXLUD as a conceptual design method for complex adaptive systems design. This chapter addresses the fifth research objective introduced in Section 1.3. This chapter presents an application of CXLUD to a systems architecting specific problem of Financial Systemic Risk Infrastructure Systems (SRITS) conceptual design program. The chapter is structured as follows. Section 6-1 provides motivation and the case study operational context. Section 6.2 describes the specific objectives of this case study discussing their relevance to the general objectives of this thesis. Section 6.3 describes the application of the CXLUD Framework. Section 6.4 closes the chapter, summarising findings and drawing conclusions from the case study.

The process that was used to obtain the results is central to this thesis, where the process refers to both the CXLUD Framework and the Creative Anticipation (CA) used to generate design concepts. In essence, the case study addresses the fifth research objective (Section 1.3). Figure 6-1 shows how this Chapter fits into the overall research, providing a roadmap for the working process.

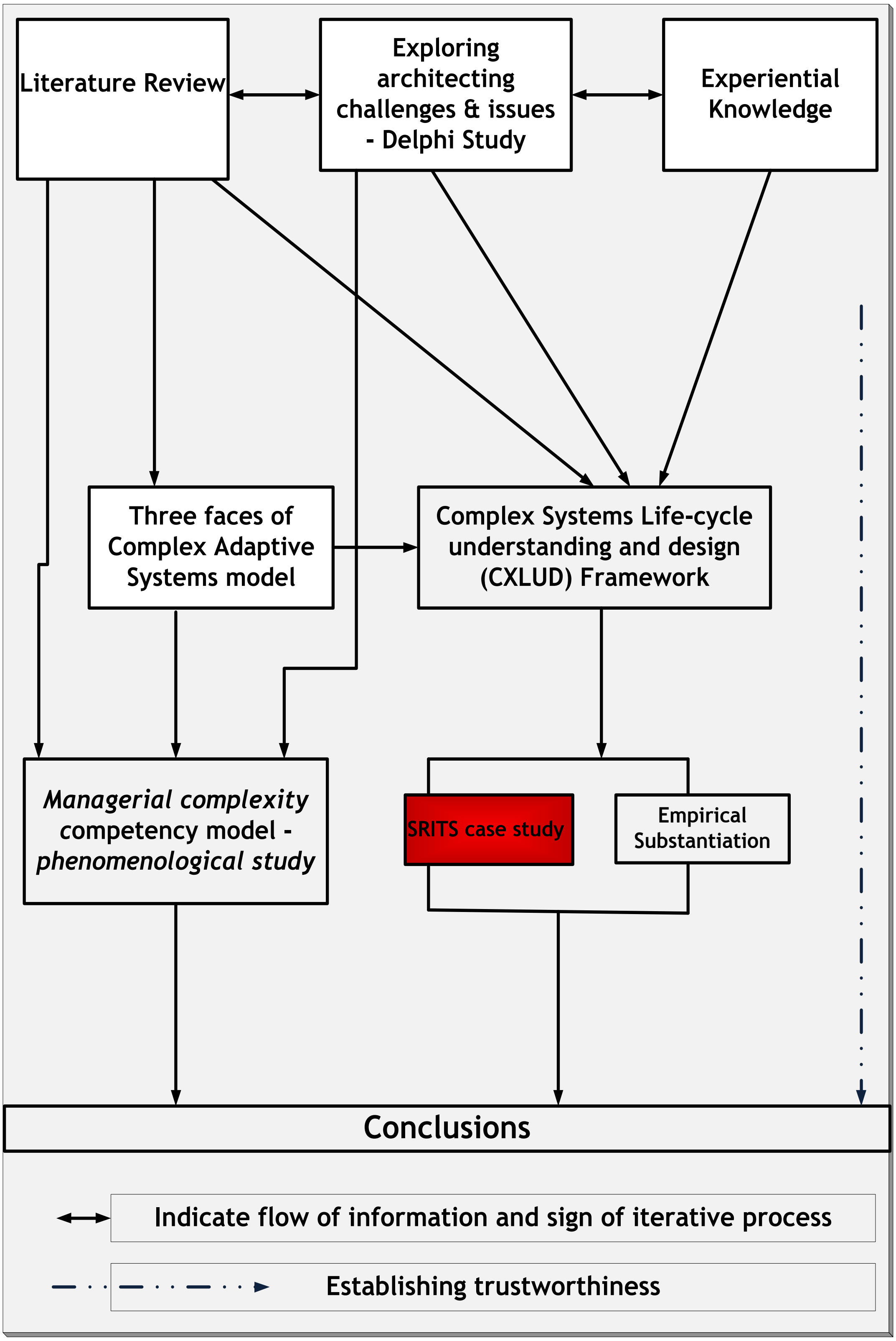

Figure 6-1: Research process with highlighted box showing current stage

6.1 Case study context

This chapter presents a case study of architectural decisions made for a Financial Systemic Risk Infrastructure Systems (SRITS) program. The research participants were Systems Architecting Team members working with a financial services company we call LSW in this thesis. LSW is a United Kingdom international bank that attaches great importance to IT architecture to manage its complex IT operations. The full name of LSW is withheld for reasons of confidentiality. The selection of LSW was driven by two factors namely, the sponsorship received (in terms of willingness to grant the researcher a direct participation role) and the fact that SRITS has characteristics of complex adaptive, which makes the program suitable for this case study. Maintaining SRITS system performance in the presence of uncertainties, such as context shifts and shifting stakeholder needs, in design and operating environments is challenging. SRITS follows an evolutionary development process - the systems are not expected to appear fully formed. Its development and existence will be evolutionary with functions and purposes added, removed and modified with experience and changes in needs and context, over time. More background details of the SRITS case study are provided in Appendix C.

6.1.1 Specific Objectives

The principal decision maker was the program manager, who was identified as the system user. Specific objective for the SRITS case study from a research standpoint was:

"Design a conceptual SRITS architecture to characterize evolutionary development strategy, with specific emphasis on value robust environment characterised by a high flux of regulatory requirements. Link this preliminary design back to the process used for the architectural study for the development and continuous innovation of systems in the SRITS program."

According to Yin, a case study is perfectly suited to illuminate why decisions were taken, how they were implemented and with what result (Yin, 2009). Since this is what this chapter aims to investigate, a case study approach was followed. A hypothesis was prepared in cooperation with the LSW department to address the specific case objective. We wanted to be explicit about what we expected and create a reference point for evaluating the outcome of the study.

6.2 Definition of the Hypothesis

The subject of the case study effort addresses the specific LSW objectives and the hypothesis for the first specific objective was formally defined as: *"The conjunction of the CXLUD framework three stages as a host complemented by Creative Anticipation enables a low-cost system design environment for the development and continuous innovation of systems within SRITS program."* The hypothesis can be considered true if the following items are met:

- The SRITS design and architecting practitioners themselves indicate that the CXLUD framework stages and steps have a positive influence on the project.
- The design processes using the CXLUD framework is considered suitable for the given SRITS project in terms of effectiveness and complexity. A key aspect of effectiveness is the frequency and quality of interaction between the different aspects of a design process.

The other subject of this case study effort addresses the second of the specific LSW objectives, strategies for designing value robustness needs into SRITS. LSW defines value robustness, in the context of this program, as the ability of the SRITS system to change easily, quickly and inexpensively in response to a wide spectrum of anticipated and unanticipated perturbation events exogenous or endogenous to the SRITS program.

Using the CXLUD framework provides low-cost and effective help for the development of value robust system architecture for SRITS program. Thus, as long as the design thinking followed in the case study and the design principles derived is thought to be helpful to the project team, it will indicate the overall feasibility and merit of the CXLUD framework. Data from feedback received about the usage of CXLUD framework from the systems architecting team members involved in the SRITS case study, as well as management commitment were used in order to examine the validity of the hypothesis.

6.3 Application of the Framework

The following subsections describe the steps carried out during the case study.

6.3.1 Design Innovation Control

For this case study, a documentary analysis of formal project documents and informal documents material on the SRITS provided by LSW was used for understanding the stakeholder’s needs, constraints and the design and operational environments. The analysis of the documents added some contextual richness to this study by grounding it in actual documents generated by LSW planning authorities.

A documentary analysis framework shown in Appendix C was developed by the researcher for use in the documentary research. Documentary data analysis consisted of manually going through each document and examining them using the documentary analysis framework in Appendix C. Aided by the information derived from the analysis, the results of the Design Innovation Control phase is documented in the next two subsections.

6.3.1.1 Need Identification

This step, defined in Section 5.3.1.1 (Need identification step) identifies mission statement and quantifies decision-maker needs. The decision-maker (i.e., stakeholder with influence over the allocation of resources for a project) is the LSW Executive Director (Program Manager for SRITS). This stakeholder is in charge of developing, acquiring and fielding the system. However, for the end-to-end utilisation of the case study, a proxy decision-maker was selected from the analyst team to represent the program manager where necessary. Table 6-1 shows the results of this analysis, i.e., descriptive goals of the SRITS case study.

Table 6-1: Descriptive Goals of SRITS case application

1. Identification of architecture features that correlate with the envisioned ability of SRITS to maintain continuous growth in an environment characterised by a high flux of regulatory requirements. SRITS must allow for new, best in class ideas and data to be integrated as these become material.
2. Development of a framework of structural, functionality and governance/integrity architecting principles that enable the identified temporal system property across the entire SRITS lifecycle.
3. Capability development - creating innovations and thinking constructs to enable a shift in the engineering mindset toward the value robustness paradigm.

6.3.1.2 Abstract information model

Following the identification of the specific objectives of the SRITS study, this section identifies key constraints capable of impacting the effective design and operation of the SRITS. The CA process was conducted with the LSW team. The outcome of the Creative Anticipation process was a set of key application stakeholders, context and constraints. Table 6-2 shows the results of this analysis. The active constraints for SRITS included constraints both on the design itself and the process of designing. The design process constraints related to the limitations on time, effort and knowledge available to the Systemic Modeling Team, Product Data Team, Systemic Risk Data Team, Summary/Visualization Team and Architecture Design Team for the project. The context for SRITS included the constraint of being a regulatory business information system. The context includes the operating environment, as well as the origin of inputs (e.g. the external data source supplier, regulatory model calculation requirement) and the destination of outputs.

Table 6-2: SRITS case application stakeholders, context and constraints

Abstract Information Model Domain	Uncertainty (i.e., constraint)
External Regulators	Responsible for the robust regulatory measures in form of regulatory algorithms calculation requirements
Government Relations.	They are concerns with assurance of the right calculation and use of approved risk model
External Data Source Supplier	No definite requirement to use external generated data sets
Systemic Modeling Team	Departure of the SRITS technical resources, lack of understanding on known knowledge
Product Catalogue Team	
Summary/Visualization Team	
Systemic Risk Data Team	
Product Data Team	
Architecture Design Team	Departure of the SRITS technical resources
	Dichotomy between stated and desired needs

Two conclusions were drawn from the outcome of the CA analysis:

1. The architecture design team itself was in the role of Project Designer and clearly had preferences that shaped the mission statement in terms of educational goals and limited temporal resources. Although the relevant stakeholders in this case study include both the external and internal team, only the project designer is considered in the analyses.
2. Depending on the stakeholder (Program Manager) needs, value robustness requirements will allow limited periods during which the envisioned SRITS system operates in a degraded or unavailable state.

6.3.2 System Lifecycle Control

After the context of the design problem is identified, the design team proceeds to develop system concepts that may meet stakeholder's needs. This is the outcome of the value driven design formulation of the next stage - System Lifecycle Control which always assumes that the required analysis has been successfully carried out in the Design Innovation Control stage.

6.3.2.1 Change Sustainment

The inputs to the change sustainment application cover the issue of the major sources of uncertainty envisioned to affect the future performance of SRITS. (The CA prompts ideation mechanism slides can be seen in Appendix C). The context for this process is provided by the system goals identified in the Need Identification step and limits for the proposed Change sustainment concepts are provided by the identified constraints/uncertainties identified in the Abstract Information Model step.

For SRITS, the change mechanisms considered are influx of regulatory requirements completeness (i.e., the entire information necessary to validate and implement them, e.g., all pre- and post-conditions) and algorithms calculation numbers are not matching up with the source data. The change agent considered in the case analysis is an external controlling agent.

The outcome of the change sustainment step is the necessary logic statements:

1. The SRITS design space should allow for multiple competitive algorithm providers to co-exist. Thus, in response to new regulatory model calculation criteria, the external model calculation controlling agent should switch over to another evaluated calculated model layer.

2. In response to a significant compromise of the SRITS calculation engine, the external controlling agent should redesign from existing design documentation.
3. Given that SRITS is envisioned as an infrastructure capability for performing infrequent early warming and monitoring operations, an allowable recovery time following a systemic failure event is one month.

6.3.2.2 SRITS Ilities Taxonomy

Recall that in the CXLUD framework definition (Section 5.5.1) the concept of the Ilities Taxonomy is a holistic view of ilities capable of enabling value robustness in an analytic frame; this enables a better dialogue among stakeholders, system architects and analysts. A simplified temporary system properties definition was given to a team of participants following the design concept and ideas steps in the creative anticipation procedure (recall the steps in Figure 5-2). The input to the Ilities Taxonomy creative anticipation exercise are the necessary change sustainment statements rendered as stakeholder's future strategic competencies and values. The output is the mapping of these future strategic competencies and values to relevant ilities.

CA Step 1 - Design problem description

The input to this first step is the output formed from the analysis of the Design Innovation Control stage. The design problem description covers the three logic statements prescribed at the Change sustainment step in Section 6.3.2.1.

CA Step 2 - Explicit lecture and prompt questioning

The detailed explicit lecture slides can be found in Appendix C. To achieve value robustness, design strategies and other enablers capable of managing and/or exploiting opportunities are required. Value robustness strategies are described and discussed.

CA Step 3 – Use Case/Data collection

At the end of the explicit lecture and during the prompt questioning, participants are encouraged to recommend alternative design concepts they thought would provide solutions to the specific design problem. Design space exploration results are analysed at each step of the study to prepare the discussion in successive rounds with participants.

CA Step 4 - Evolving but partial design – Generated Concepts

With a considerable field of knowledge and a broad body of literature about a specific system properties or ilities and to make a contribution to knowledge and also provide the participants with a better way to discuss the merits of each generated system property, the case study team built a system taxonomy for reviewing all possible system characteristics. Thus, the study evaluates the design space of SRITS architecture temporary system properties across two dimensions (Table 6-3), namely change related and non-change related ilities, each of which is capable of providing insight into understanding a system's change over time and giving an important understanding of value of SRITS through changing contexts or environments.

Table 6-3: SRITS Generated Ilities Taxonomy

1	The "Change related ilities" are those that enable system design that can be intentionally designed to change. Examples are evolvability, flexibility, adaptability, modularity, multiability, interoperability. The SRITS team asserted that consideration for inclusions of evolvability and anticipation in SRITS hinges on the expected long system development cycle and strong variability in the calculation metrics for SRITS secondary function as an early warning system.
2	The "No-change related ilities" limits the use of a change mechanism or enables the use of a resistance mechanism. This includes robustness, manageability maintainability and survivability.

Careful high level concept generation and pruning of the generated logic statements led the project team to two ilities: evolvability and adaptability. The context for this process is provided by the definitions of the ilities relative to the change sustainment statements. Evolvability was defined as the ability of the SRITS architecture to be changed between generations in response to general shifts in context or needs. Adaptability on the other hand, is defined as the ability of SRITS to be changed by another system. A value hierarchy was created in Figure 6-2 in the form of a Function Means Tree. The concept of evolvability and adaptability was selected due to their nature and ability to fit within the SRITS constraints. In the end, the decision maker agreed that the proposed value hierarchy accurately mirrored values essential to SRITS. Successful SRITS systems will use combinations of these approaches to maintain their integrity in a changing and unexpected environment.

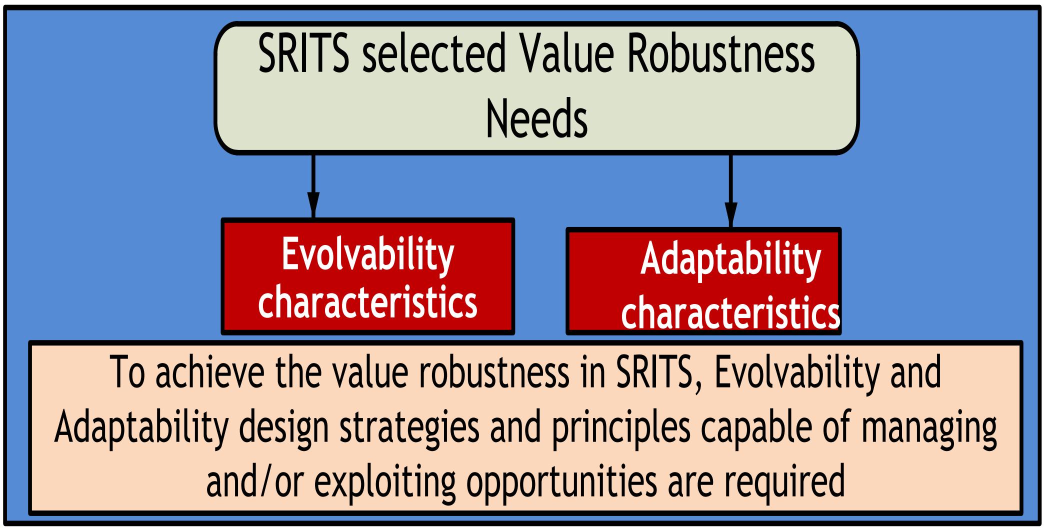

Figure 6-2: Function Means Tree for selected need for value robustness

To achieve sustainable value in SRITS, evolvability and adaptability design principles capable of managing and/or exploiting opportunities are required in the SRITS architectural model.

The high level strategy underlying SRITS approach to designing a valuable system is to strategically combine elements of robustness, evolvable and adaptive reaction in the architecture of the system. This high level strategy led to a number of design principles that influenced the value robust architecture definition for the proposed SRITS. These are explained in the following sections.

6.3.2.3 SRITS Architecting Design Principles Control

The goal of the third case study objective is to develop a framework of structural and behavioral principles that enable evolvability across the entire lifecycle of SRITS. The context for this process is provided by the Change Sustainment generated logic statements and limits for the proposed design principles are provided by the identified Ilities Taxonomy concept. The postulated goal of SRITS system architecture is to enhance the ability of the system to be ready for change in response to a changing environment. Within the context established by LSW, any prescribed architecting principles must reflect the three fundamental sets of properties identified in the Need Identification sessions (Section 6.3.1.1 and Table 6-1: Descriptive Goals of SRITS case application) namely: structural, functionality and governance/integrity. Architecture design principles that enhance these properties are considered in the next session of the CA sessions to guide architectural design.

CA Step 1 - design problem description

For the SRITS case study, the identified temporal system property – evolvability and logic statements inform the generation of system design principles that mitigate the impact of each constraint. To define a set of principles, the concept of a principle must be clearly understood and defined first. Thus, the intent of the principles is to give both designers and evaluators of SRITS design process a clear idea of what qualities the SRITS systems must meet, rather than a list of individual specific items.

CA Step 2 - Explicit lecture and prompt questioning

The design space exploration was set-up with the theme of looking at the SRITS specific architectural design principles objective.

CA Step 3 – Use Case/Data collection

At the end of the explicit lecture, participants were encouraged to recommend alternative design concepts they thought would provide a solution to the specific design problem. The list below represents a summary of complete ideas from the transcript analysis of the creative anticipation session.

- Functional Exaptation
- Adaptive Boundary
- Requirements Balance
- Documentation Completeness
- Repeatable and Documented Procedures
- Duplication and Divergence
- Targeted Modularity
- Under design of components
- Anticipation

CA Step 4 - Evolving but partial design

Figure 6-3 is the resultant descriptive framework summarizing the design principles for architecting SRITS as considered by the case study team. Figure 6-3 reflects the selected SRITS system architecture needs (i.e., robustness, evolvability or adaptability - ability to accommodate change) and associated design principles. A system architecture in general constitutes a framework for implementation, and can be determined with reference to the envisioned process, process model, and execution algorithm as well as technology. Thus, the design and control of SRITS involves several complementary viewpoints identifying the decision made at each step and citing the major architecture principles from which it is derived. For this thesis purpose, it is grouped for better discussion as: enhancing functionality, enhancing governance or system integrity and system structure and interaction mechanism. The grouping serves to illustrate how it may be used as a knowledge base to support complex system engineering anticipatory capacity of an engineering organisation.

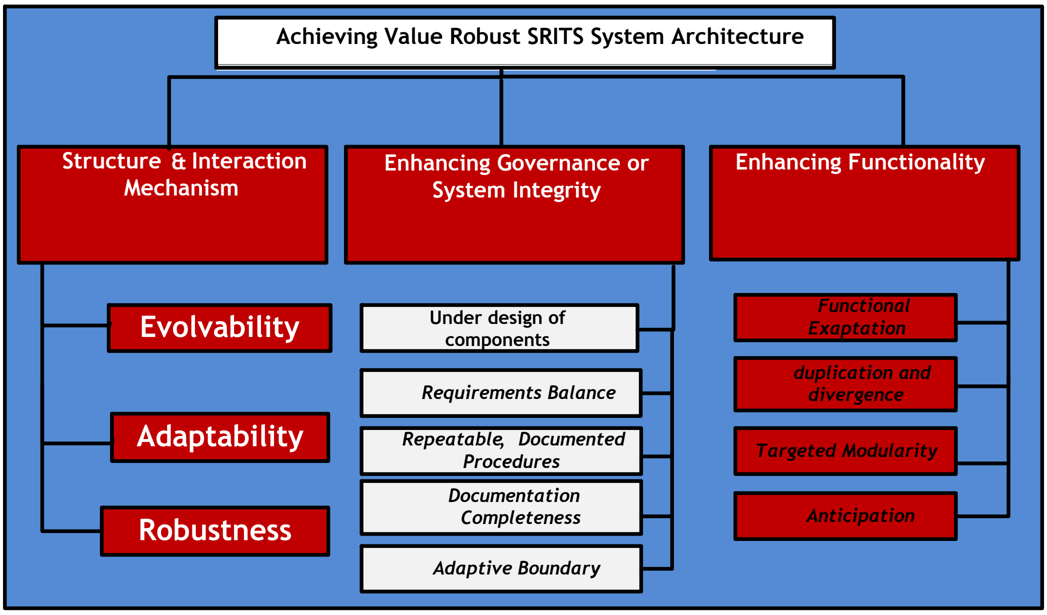

Figure 6-3: Framework of Design Principles prepared for the case study application

The design principles explored and analysed at the CA sessions as discussed in this section apply to both adaptability and evolvability. Selected architecture design principles that enhance the 'enhancing functionality' and 'enhancing governance or system integrity' properties are considered. The design principles list is not intended to be exhaustive. These concepts would then facilitate the architecture analysis and development described by Maier and Rechtin (2009) as well as subsequent design decisions in the context of the ilities taxonomy defined (e.g. adaptability, evolvability) and for handling uncertainties. In the following paragraphs, each principle is described.

The following principles influence the enhancing functionality properties of the envisioned SRITS system:

Functional Exaptation: Aims to achieve both evolvability and adaptability. The principle acknowledges that agents are able to innovate either by introducing new sources or by changing the sources of the artifacts they are using, i.e., exaptation is characterized by a process of change, a process in which all the structural conditions necessary for the new functionality are developed.

Duplication and Divergence: For the purpose of this thesis, the principle of Duplication and Divergence states that the architecture should allow the existence of a variety of more or less sophisticated forms of information processing and control which can operate concurrently. This principle is also called the principle of decentralization and is a key factor in anticipation and adaptability. Based on loose coupling and strong cohesion a decentralised distribution of control, information, resources, attributes and properties within the system architecture strengthens the capability of the SRITS system to rapidly adapt to its environment and to respond semi-autonomously to changing requirements.

Targeted Modularity: this relates to the principle of using modularity in selected components or subsystems of SRITS. The importance of targeted modularity lies in the fact that without it, a small change in one place can require many compensatory changes elsewhere; changes ripple through the system design. Thus, the targeted modularity principle is fundamental to achieving anticipation and evolvability in SRITS.

Anticipation: The principle of Anticipation is fundamental to the design and implementation of effective SRITS interfaces. Facilitate gaining control of the interactivity and bring to the user all the information and tools needed for each step of the process. The principle involves exploring different options, and receiving all possible feedback from the system.

The following principles influence the enhancing governance or system integrity properties of the envisioned SRITS system:

Adaptive Boundary: This acknowledges that segments of the architecture design should be allowed to adapt while others may be required to be static. The principle acknowledges that architecture takes on new meanings in both different times and spaces; negotiation and adjustment with other aspects of the systems involved is always required. Neglecting to articulate and negotiate potential conflicts will result in disappointing a particular stakeholder - usually the one without the explicitly stated objective. The associated outcome description is architectural scoping of where the level of adaptation occurs and identification of potential system and environmental impacts.

Requirements Balance: In the context of SRITS, there are two important reasons for the principle of balanced requirements. First, is the need to maintain SRITS architecting or system development within its constraints. Secondly, to ensure that no single requirement or decision-maker imposed requirement is driving the design of SRITS (system) architecture, but rather there is a balance in the design. Therefore, this principle necessitates that the design requirements for the system architecture be specified before they can be applied. Developing requirements is an iterative process, just like any other system design problem; therefore, to meet this principle, the system architect or design team is expected to iterate on the requirements of the other principles and then balance them.

Documentation Completeness: Design for change requires anticipation of the ways in which the system might be required to change including additions, deletions and modifications. The requirement is to structure the system to facilitate change at all levels. Thus, when the design team is composed of different members, sometimes documentation is all that exists for the system change team to work from. By capturing as much information as possible in documentation, even if it takes more time, the adaptable or evolvable system redesign process might be less difficult and provide a more positive return on the extra resources spent on documentation.

Repeatable and Documented Procedures: The principle of repeatable and documented procedures means that the techniques used to construct a component should permit the same component to be completely and correctly reconstructed at a later time. Repeatable and documented procedures support the creation of a component which is identical to the component created earlier that may be in widespread use.

Under designing of components: The expected constant changes in the data and calculation metrics for risk model promotes the needs for adaptability and evolvability in the SRITS design, thus under-designing the risk model to this constraint with the intent of easing the future re-design process was considered important.

In the next section we explain how these principles were applied in the creation of the SRITS architecture. It is important to note that the architecture has incorporated a number of tunable parameters (for instance, amount of redundancy, amount of diversity, number of exaptation layers). These tunable parameters allow for cost-benefit trade-offs, making the value robust architecture applicable to contexts that have different evolvability and adaptability requirements from the SRITS described.

6.3.3 Architecture Realization Control

In this section we present a summary of the key aspects of the SRITS value robust architecture we designed or derived during the case application. The value robust enabled SRITS is required: to routinely allow for new, best in class ideas and data to be integrated, avoid unplanned obsolescence and ultimately facilitate meaningful information sharing.

Figure 6-4 shows the derived value robust-enabled SRITS architecture. The architectures proposed are hybrid distributed systems with sub-intelligent agents (i.e., human in the case of SRITS). The core SRITS (i.e., resultant models) uses redundant service providers, represented by the different layers. The control mechanism proposed for the development and sustainability of the SRITS architecture and summarized in Figure 6-4, is an ongoing series of competitions for both the modeling and the summary components of the system. The resultant structure (Figure 6-4) in terms of components, connections and constraints of SRITS is organised on different layers. The layered structure is envisaged to guide the SRITS architecting team to make decisions about building and evolving SRITS systems.

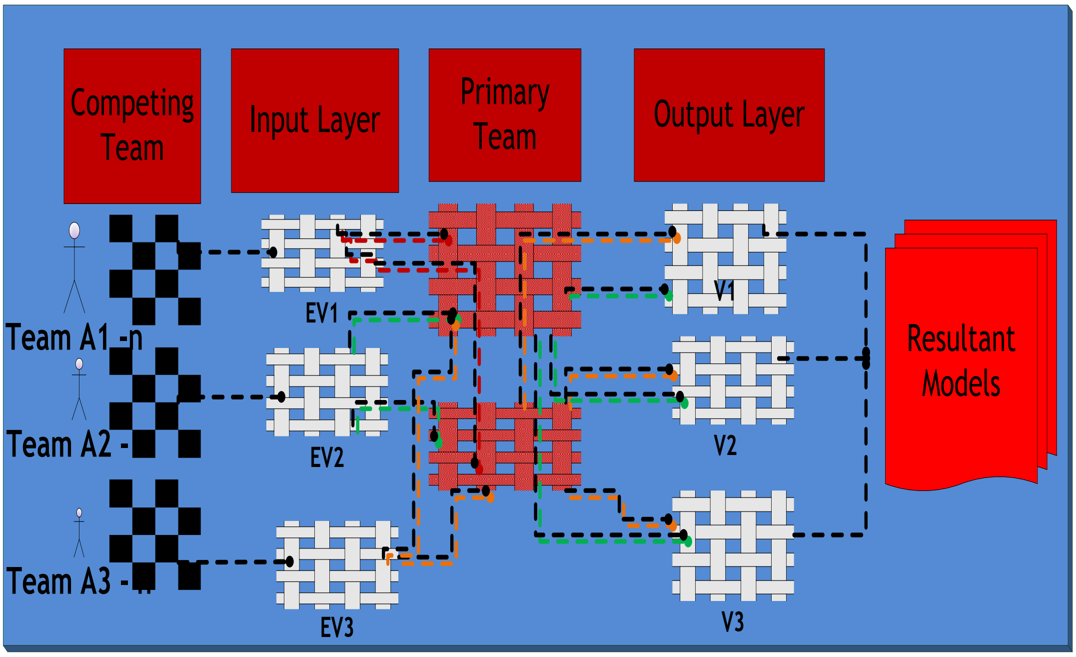

Figure 6-4: Schema of the derived layered-network centric SRITS architecture

For simplicity, the case application considered a scenario in which the Input Layer (EV1 to EV3) can accept a high number of different inputs from Competing Teams (Team A1 – N, Team A2 - N and Team A3-N). The Competing Team layer is adaptive teams that are working on gaining an understanding of the SRITS design problems and solution. It is envisaged to determine an optimum recovery and growth path, contributes to the knowledge base and the learning tasks. The proposed model creates a system for allowing different teams to create competing systemic-risk models for SRITS consumption.

The response from the Input layer is deterministic in general. The Primary Team Layer is part of the larger SRITS where data and models are processed and interpreted. The Primary Team layer facilitates system control and systems control is facilitated by positive and negative feedback at every level. The information received from the Input Layer can be widely diversified. The capacity to admit this variability confers evolvability and adaptability on the system. The primary team layer is capable of filtering information, interpreting commands and inferring knowledge. The primary team layer is the one that processes the information and ultimately decides on a strategy to address failures.The primary team layer are able to innovate, evolve and ultimately adapt either by introducing a new competing team layer or by changing the input layer supplied artefact. These will ultimately determine the value of the resultant models. The activities of the different layers increase the opportunity for enablingthe value robustness in SRITS designs.

6.4 Chapter Summary

The case study presented here is focused on the systems architecture of Financial Systemic Risk Infrastructure Systems (SRITS). Sections 6.1 and 6.2introduced the problem, provided motivations for the analysis and outlined specific objectives to be achieved by the case study. Section 6.3 described the step-by-step application of the CXLUD framework to the case study as per the theory outlined in Chapter 5. More details on the SRITS program, organisation and conduct of the case study and creative anticipation material used in the implementation are available in Appendix C. The selection of the SRITS as the case project was driven by two factors namely, the sponsorship received (in terms of willingness to grant the researcher a direct participation role) and SRITS is characterised as a large scale complex adaptive system, which makes the program suitable for the research case study.

A specific feature of this case study is the presence of intelligent agents and lack of clarity in the definition of the functional intent with direct impact on envisioned value delivery to stakeholders as expressed by the goals. The questions of interest considered in this case study led to the development of recommendations on the architecture of SRITS. Main highlights from the different stages of CXLUD framework are discussed in Section 6.3.1 (Design Innovation Control), Section 6.3.2 (System Lifecycle Control), and Section 6.3.3 (Architectural Realization Control).

The following observations were made based on the observation and direct participant information collected throughout this case study:

- The use of CA as a qualitative design concept generation and ideation mechanism method in this project led to the understanding of essential relations between temporal system properties, also called ilities and system architectures from the perspective of the LSW team which would have otherwise been overlooked at the early conceptual phase of the SRITS design.
- Bringing value robustness properties into the system conceptual design is not the sole duty of requirements engineers and system architects. The involvement of system end users (in the case of SRITS risk analysts) and senior management in the process under the leadership of system architects had a positive impact on the project.

There are notable limitations to the success of the case study. For instance, personal attitudes of the participants and their level of understanding of the CXLUD might have influenced the architecting design principles model developed and thus reduced the validity of the case study. Also, while the CXLUD framework approach is low-cost, logical and based on sound theory, it demands more subjective inputs about their value judgments and is time-consuming in setting up the process. Nevertheless, we argue that based on the case study it is possible to state that: in performing the CXLUD stages and steps activities dutifully can bring the following benefits:

- Allow for ready communication among designers and stakeholders.
- Collaborative analysis of system design and architecting issues.
- Generation of alternatives design solutions set which can be kept much longer.
- Provides design environment where design issues can be explored deeper rather than the normal point requirements scenarios.

- Provides an opportunity for refining generated alternative design solutions in the context of system operational objectives.
- Provides for integration of design and requirements specification activity to be performed much closer together and in tight communication with each other.

The SRITS design team agreed that both the explicit lecture and prompting mechanism significantly improved the generation of valuable SRITS design concepts. They also had positive user satisfaction with the SRITS design process as a result of the CXLUD constructs.

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CHAPTER 7 SUBSTANTIATING THE CXLUD FRAMEWORK

This chapter addresses the concluding part of the fifth research objective introduced in Section 1.3. The purpose of this research objective is the empirical validation of the CXLUD framework developed in Chapter 5. The final thrust of the CXLUD case application is to garner targeted, more in depth insights from systems designers, engineers and project managers. The study was based on an exploratory questionnaire. Questions were structured with respect to the metrics defined in Section 7-1. The cognitive value of the findings is estimated as follows:

- Participants are experienced complex adaptive systems design and management experts who know the challenges of complexity management projects. For that reason, it is assumed that they are able to validate a CXLUD's potential applicability even if they did not apply the proposed CXLUD in real-life projects.
- A high significance of the assumed effectiveness is expected as the participants have experienced other design procedures, design processes and methodologies in practice.
- Not all of the participants participated in the case study application of CXLUD in practice presented in Chapter 6.
- The participants are all of graduate education level and have more than two years of experience architecting and managing in complex adaptive system environments. For that reason, they possess a sound theoretical skill that is the basis for a system design methodology validation.

The remainder of the chapter is organized as follows: Section 7.2 provides a detailed analysis of the results gathered from the substantiation process. Section 7.3 concludes the chapter and states the limitations of this chapter study. The substantiation approach including the procedure for gathering feedback, substantiation questions and participant's guidelines can be found in Appendix D. Figure 7-1 shows how this Chapter fits into the overall research process.

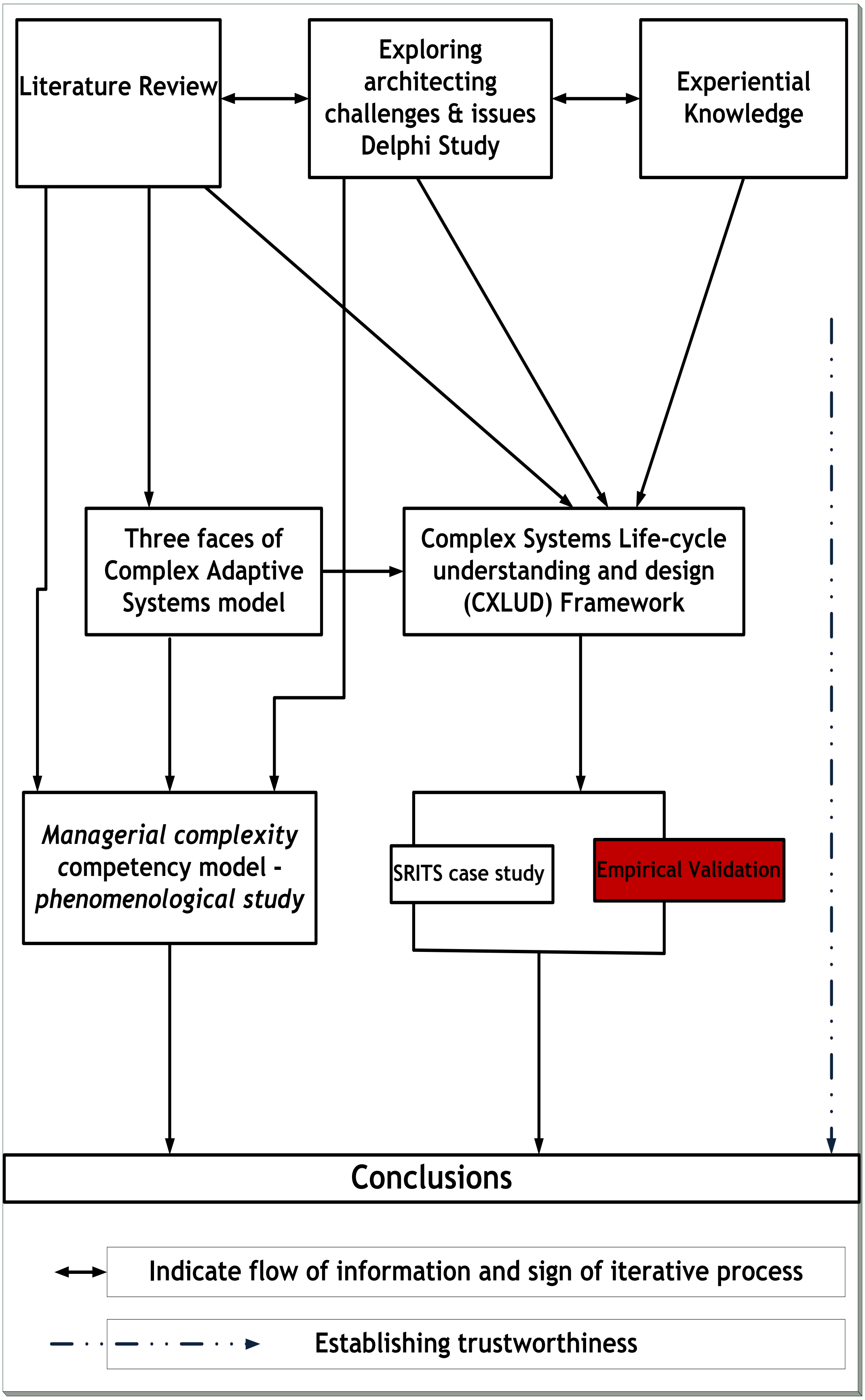


Figure 7-1: Research process with current stage highlighted

7.1 General Character and Scope

The substantiation process and other supplemental material are provided in Appendix D. In this substantiation study, we assess the goodness of the CXLUD framework based on (1) practicality, (2) necessity, (3) understandability, (4) completeness and (5) effectiveness. We define these validation metrics as below (Table 7-1):

Table 7-1: CXLUD Empirical Validation Metrics

Validation metrics	Definitions
Practicality	Framework would be practical and feasible to use.
Necessity	Each of the stages or steps in CXLUD as defined encompasses a set of system design practices and concepts. To what extent those practices and concepts are relevant and correctly assigned.
Understandability	The ease with which the concepts and stages in the framework can be understood.
Completeness	Sufficiency of the framework with respect to meeting stated objectives.
Effectiveness	Producing or guiding the production of the intended or expected results – which depend on the envisioned system characteristics.

7.2 Results and Analysis

The results were presented in four main sub-sections. Each is summarised below.

7.2.1 Participant's Background

The first step in our analysis was to classify the 21 participants who responded to the questionnaire based on their roles and positions; the participants fell into three categories:

1. System Architects/Engineers: Twelve of the participants were classified under what is called system architects/engineers.

2. Project/Program Management: Four of the participants were program and project managers.
3. Risk/Policy Consultants: Five of the participants were systemic risk and policy consultants and business analysts.

The participants were all involved with the SRITS project or generally working for LSW as defined in Chapter 6. The next step was a categorisation based on years of experience. Table 7-2 shows the number of participants by role and experience and highlights the relation between the two categories; i.e., based on their years of experience, the participants were also divided into three groups:

1. 1-2 Years: Only one participant had between 1-2 years of experience with complex systems concepts and architecting.
2. 3-5 Years: Eleven of the participants had between 3-5 years of experience with complex systems concepts and architecting.
3. 6-12 Years: Nine of the participants had between 6-12 years of experience with complex systems concepts and architecting.

Table 7-2: Categorisation of participants by their roles and years of experience

Groups	1-2 Years	3-5 Years	6-12 Years	Total
Program/Project Managers	0	2	2	4
Risk/Policy consultants	0	3	2	5
Systems Architects/Engineers	1	6	5	12
Total	1	11	9	21

From Table 7-2, several interesting observations concerning the grouping of the participants are as follows: most of the practitioners that participated have 3 or more years of experience and most of Systems Architects/Engineers have 3-5 years of experience. Participants with over six years were considered important to the success of the validation effort since this group represented the experts and leaders. They possessed substantial knowledge about challenges of complex adaptive system design and were therefore better able to assess the overall performance of the CXLUD Framework. The remaining participants were also important to the validation effort, because they assessed how the framework met their needs for guidance throughout the design and support process. As a total group, the participants represented the range of experience usually encountered in system design projects.

7.2.2 Research Overall Analysis

For the assessment categories, the categorical variables (attributed data) have been used to represent and analyse the feedback of the experts.

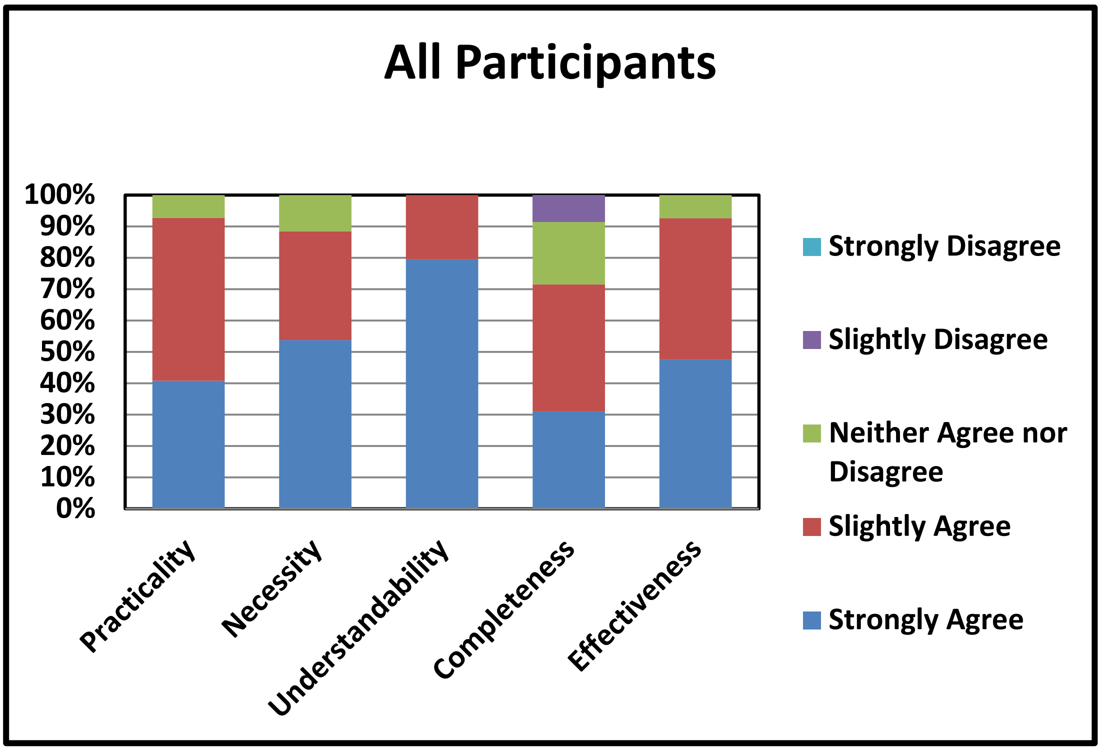
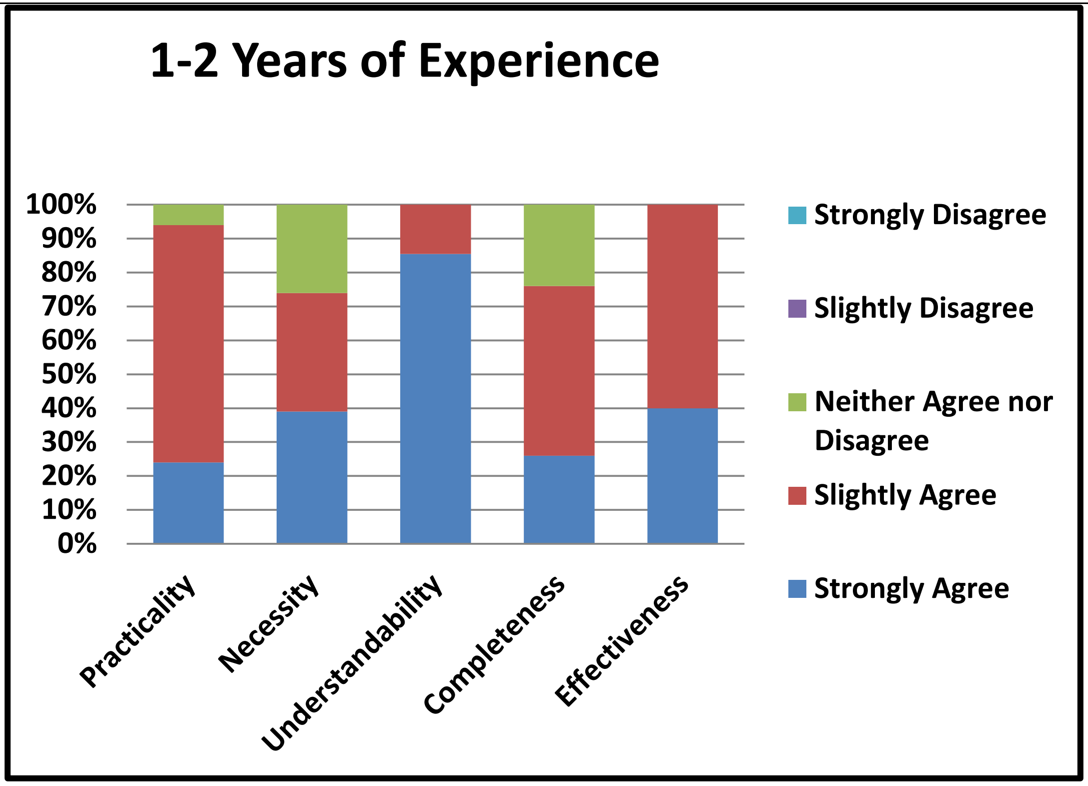


Figure 7-2: Overall results for the different Stages in the CXLUD Framework

Graphs have been used to present the categorical data by counting the number of observations that fall into each group. Table data entries are converted into percentages. As Figure 7-2 shows, the majority of participants either strongly agreed or slightly agreed with all five aspects of the CXLUD framework. What is encouraging is that not a single participant strongly disagreed with any aspect of the CXLUD Framework and only a minor percentage of the participants slightly disagreed with its completeness.

7.2.3 Research Findings - Understandability

Here, the responses of the experts have been analysed to determine the result indicators. As Figure 7-2 shows, a total of 78% strongly agree; 22% slightly agree (i.e., all participants reported that the framework was clear, well thought out and easy to understand giving satisfactory feedback).Thus, the overall assessment in this particular category was considered satisfactory, since a total of 50% or more of all the experts reported or indicated satisfactory feedback. When categorized by years of experience, as Figure 7-3 shows, a trend emerged: participants with between 1-2 and 6-12 years of experience more strongly agreed that the CXLUD processes were understandable than participants with 3-5 years of experience. As Figure 7-4 shows, the results categorized by role also reflect a mixed trend. Since the CXLUD framework provides guidance about system design effort, it is logical and expected that the system architects/designers would understand the process more than the managers. However, this is not the case. There was an even distribution between the designers and the managers. As shown in Figure 7-4, in the Risk/Policy Consultants role category 78% strongly agreed while 22% slightly agreed, in the Program/Project Management category 50% of the participants strongly agreed and 50% slightly agreed and Architects/Engineers with 48% strongly agreed and 52% slightly agreed. The Program/Project Management practitioners were much stronger in their agreement to its understandability.



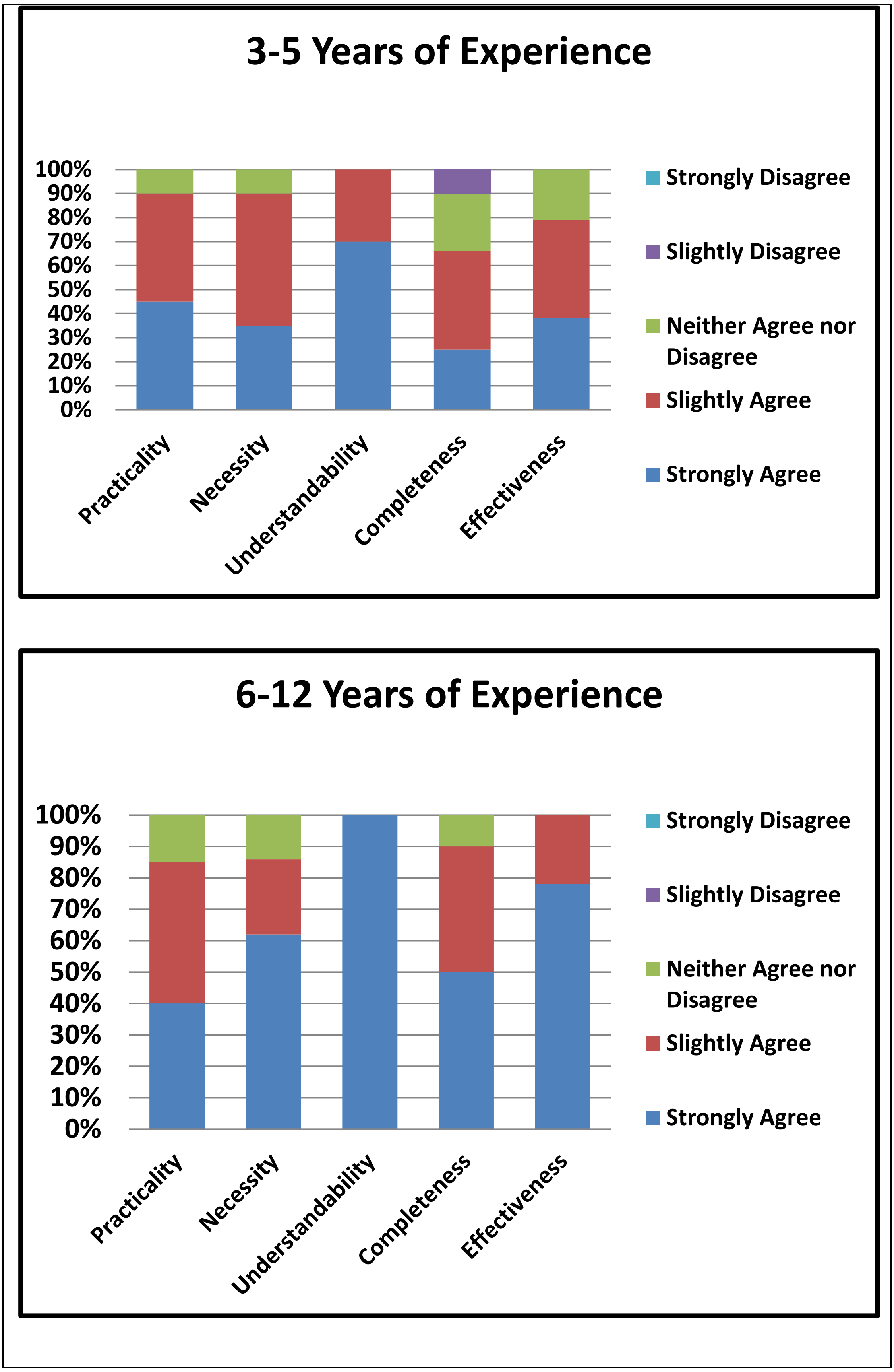


Figure 7-3: Empirical results categorised by years of experience

7.2.4 Research Findings - Practicality

While none of the participants disagreed about the practicality of the framework, as Figure 7-2 shows, the strong consensus seen for understandability fell, with 41% of the participants strongly agreeing, 50% slightly agreeing and 9% remaining neutral. The overall assessment in this particular category is however still considered satisfactory, since more than 50% of all the experts reported or indicated satisfactory feedback.

Interestingly, the results were almost the same regardless of the years of experience as Figure 7-3 show. Participants with 3-5 years and with 6-12 years of experience have close agreement rates (90% and 85%, respectively) about the practicality of the framework. Participants in the 1-2 years of experience range gave 92% agreement about the practicality of the same framework. However, when classified by roles as shown in Figure 7-4, the results did vary. In the Risk/Policy Consultants role category 58% strongly agreed while 33% slightly agreed, in the Program/Project Management category 15% of the participants strongly agreed and 73% slightly agreed and Architects/Engineers with 25% strongly agreed and 65% slightly agreed. The risk analyst and compliance consultants were much stronger in their agreement to its practicality.

7.2.5 Research Findings - Necessity

Returning to Figure 7-2, 53% of all participants strongly agreed, while 35% slightly agreed and 12% neither agreed nor disagreed. The overall assessment in this particular category is considered satisfactory, since a total of 50% or more of all the experts reported satisfactory feedback.

As Figure 7-3 shows, when categorised by years of experience, the results were almost the same regardless of the years of experience. Participants with 3-5 years and with 6-12 years of experience have close agreement rates (90% and 85%, respectively) about the necessity of the framework. Participants in the 1-2 years of experience range gave 73% agreement about the necessity of the same framework.

Figure 7-4 shows that when categorised by role, the results exhibit a different trend in that 62% of system architect and engineers (50% strongly agreed and 12% slightly agree), management experts (25% strongly agreed and 63% slightly agreed) and risk/policy consultants agreed on the necessity for the CXLUD framework with 92% satisfactory level with (52% of the participants chose strongly agreed and 40% chose slightly agreed).

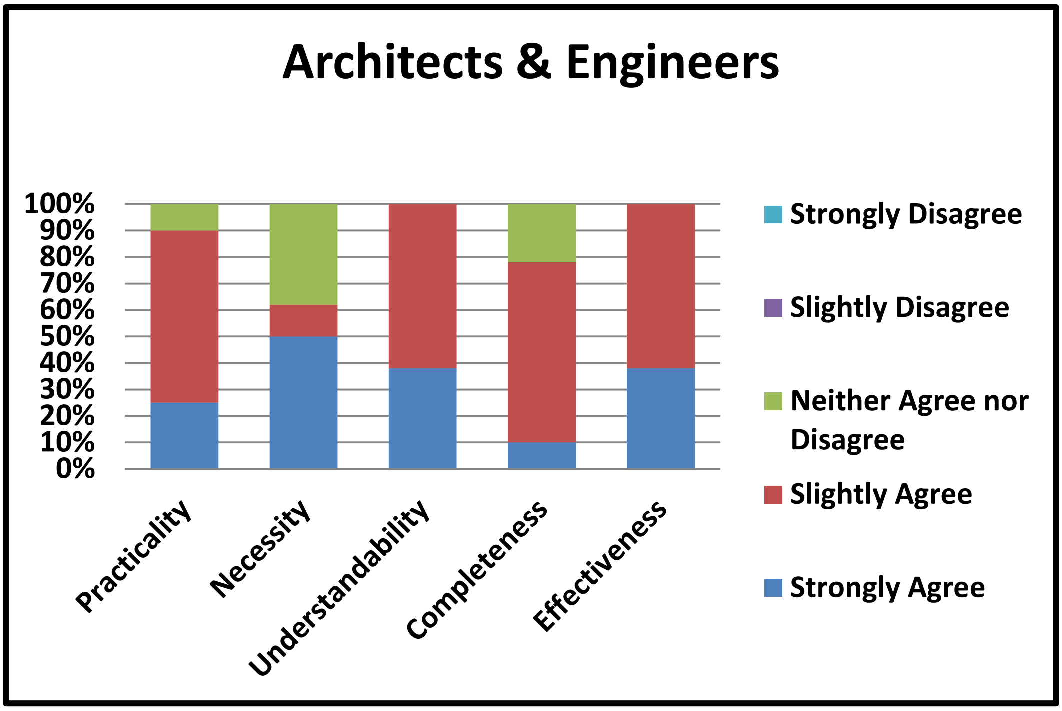
7.2.6 Research Findings - Completeness

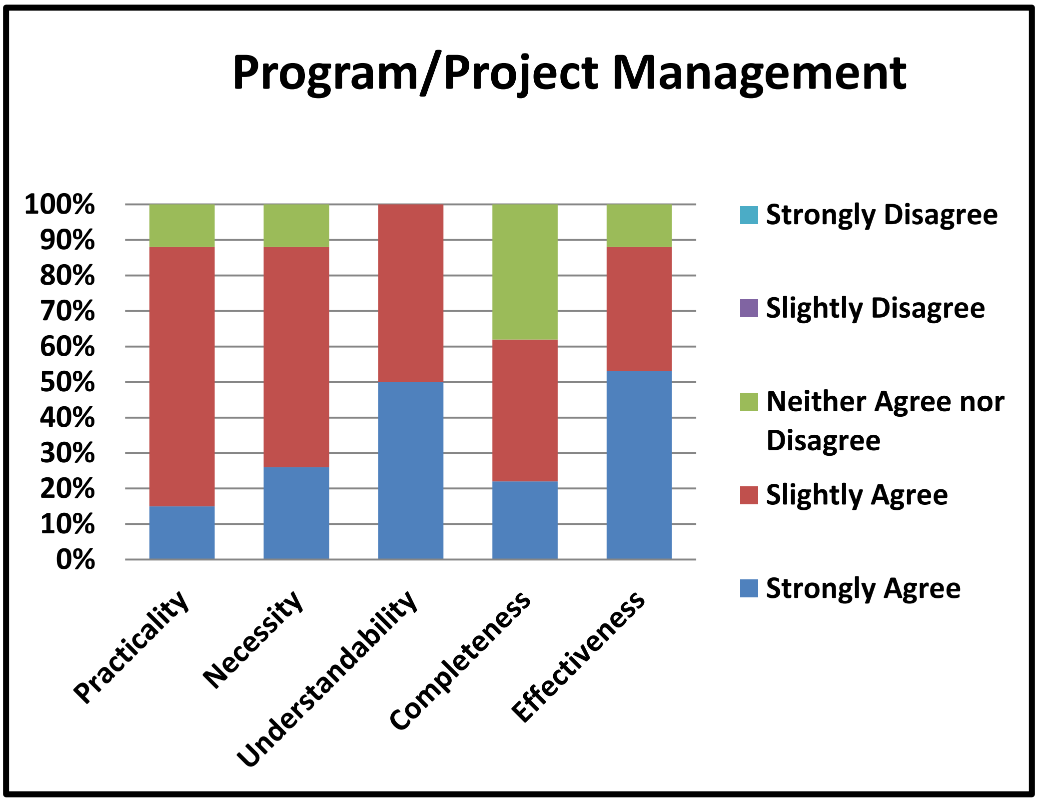
From Figure 7-2, 32% of the participants strongly agreed, 40% slightly agreed, 20% neither agreed nor disagreed and only 8% slightly disagree that the CXLUD stages and steps are comprehensive enough to reflect the various steps most engineering enterprise go through to reach complete conceptual architecture design. The overall assessment in this particular category is considered satisfactory, since a total of 50% or more of all the experts reported or indicated satisfactory feedback. When categorised by years of experience, the results exhibit a trend. Participants with 1-2 years and with 3-5 years of experience have close agreement rates (76% and 65%, respectively) about the completeness of the framework. When categorised by role, the results exhibit a different trend in that 78% of system architect and engineers (10% strongly agree and 68% slightly agreed), management experts (22% strongly agreed and 40% slightly agreed) and risk/policy consultants (42% strongly agree and 40% slightly agreed), agreed on the adequacy of the completeness of the CXLUD framework giving a satisfactory level.

7.2.7 Research Findings - Effectiveness

Figure 7-2 also shows that the participants gave a satisfactory response to CXLUD framework components with regards to its effectiveness, i.e., capable of achieving what is projected to do. A total of 49% of the participants strongly agreed and 42% slightly agreed, while 9% were neutral. As Figure 7-3 shows, when categorised by years of experience, the results exhibit a trend. Participants with 1-2 years and with 6-12 years of experience have agreement rates (100% and 100%, respectively) about the effectiveness of the framework. In the 3-5 years of experience, 38% strongly agreed, 50% slightly agree and 22% neither agree nor disagree.

When categorised by role, the results exhibit a different trend in that 100% of system architect and engineers (38% strongly agreed and 62% slightly agreed), management experts (52% strongly agreed, 36% slightly agreed and 12% neutral) and risk consultants agreed on the adequacy of the completeness of the CXLUD Framework with 90% satisfactory level (58% strongly agreed, 32% slightly agreed and 10% were neutral).


Architects & Engineers
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Practicality
Necessity
Understandability
Completeness
Effectiveness
Strongly Disagree
Slightly Disagree
Neither Agree nor Disagree
Slightly Agree
Strongly Agree


Program/Project Management
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Practicality
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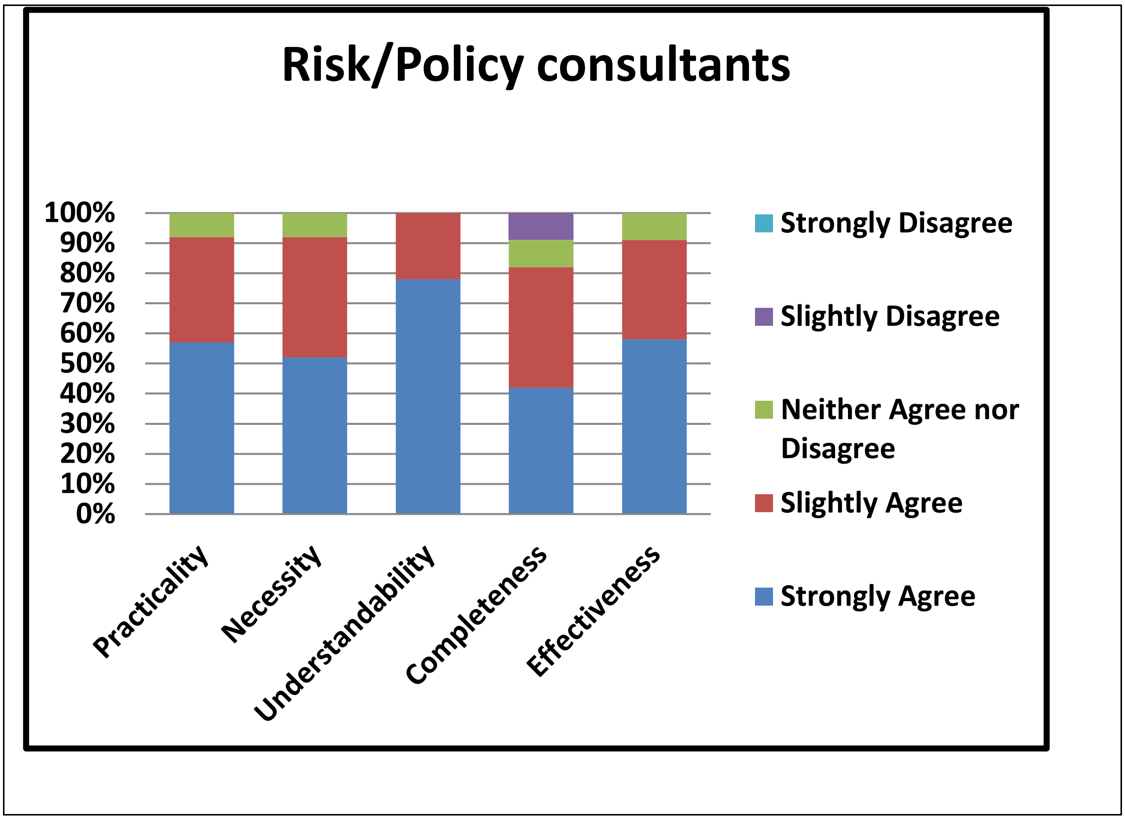

Figure 7-4: Empirical results categorised by Role

7.3 Chapter Summary

This study set out to empirically examine the CXLUD Framework from the perspective of architectural design with it. The CXLUD definitions were validated using questionnaires with system design and process-experts. The intention was to gain findings with respect to the CXLUD's practicality, necessity, understandability, completeness and effectiveness.

The Framework was presented to over 20 members of the complex system design management community to gather feedback about their goodness. The results of the participants' feedback are examined from two perspectives, the first being the role or position of the participant, and the second being their years of experience. Figure 7-2 illustrates that, in general, the participants were mostly in agreement with regard to practicality, necessity, understandability, completeness and effectiveness. However, some variability is observed among the participants concerning completeness. We conjecture that this is due to the fact that each participant has different experiences, depending on their role, years of experience and the projects in which they have been involved. As a result, each participant places a different priority on the use of practices as reflected in their experiences.

These beneficial insights and feedback have led us to recognise the utility of, and need for, the flexibility to tailor the components of CXLUD to fit experiences and perhaps business goals.

When examining the results classified by role, it is important to note that system architects and engineers had more positive feedback, in general, than the other positions. The feedback obtained from this substantiation process is promising and conveys the perceived goodness of the framework along with each of its components.

What is noteworthy about the results gathered from the experts is that most of the participants agreed satisfactorily to all aspects of the CXLUD Framework. These results underscore the perceived relevance of the framework and substantiate its validity. While we recognize that the CXLUD framework has yet to reach the envisioned potential, the researcher is encouraged by the comments given from the system design and management community.

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CHAPTER 8 BUILDING A MANAGERIAL COMPLEXITY COMPETENCY MODEL

This chapter addresses the second research question and the sixth research objective introduced in Section 1.3 and repeated below:

Research objective 6: Undertake a study to explore how complex adaptive system project leaders perceive and describe the lived experiences of coping with managerial complexity.

Project decision makers in complex adaptive systems design and operations are placed in situations that are increasingly complex, making decision-making and problem-solving processes multifaceted. Chapter 1 described the lack of existence of appropriate dynamic systems competencies in the workforce such as complex adaptive systems thinking as a threat to a successful design and operation of value delivery processes. The presence of a human as an intelligent subsystem that forms requirements and makes decisions in complex adaptive systems is one of the basic reasons which make it difficult for such systems to be described or managed by formalised methods.

From an industry perspective, the empirical studies of systems architecting challenges and issues presented in Chapter 4 reveal that ‘effective coordination strategies for managerial complexity issues’ are an important architectural design challenge and issue facing engineering organisations. In addition, insights from literature indicate that current program and project management bodies of knowledge or methodologies are incomplete as they do not sufficiently address complexity, creating a gap between theory and practice. Success in complex adaptive systems design and operational activities can be increased if project leaders are encouraged to apply complexity thinking in making managerial decisions about their project.This chapter has the focus of contributing to the existing bodies of knowledge in managerial complexity by exploring and defining a new competency model. Figure 8-1 shows how this Chapter fits into this thesis overall research process.

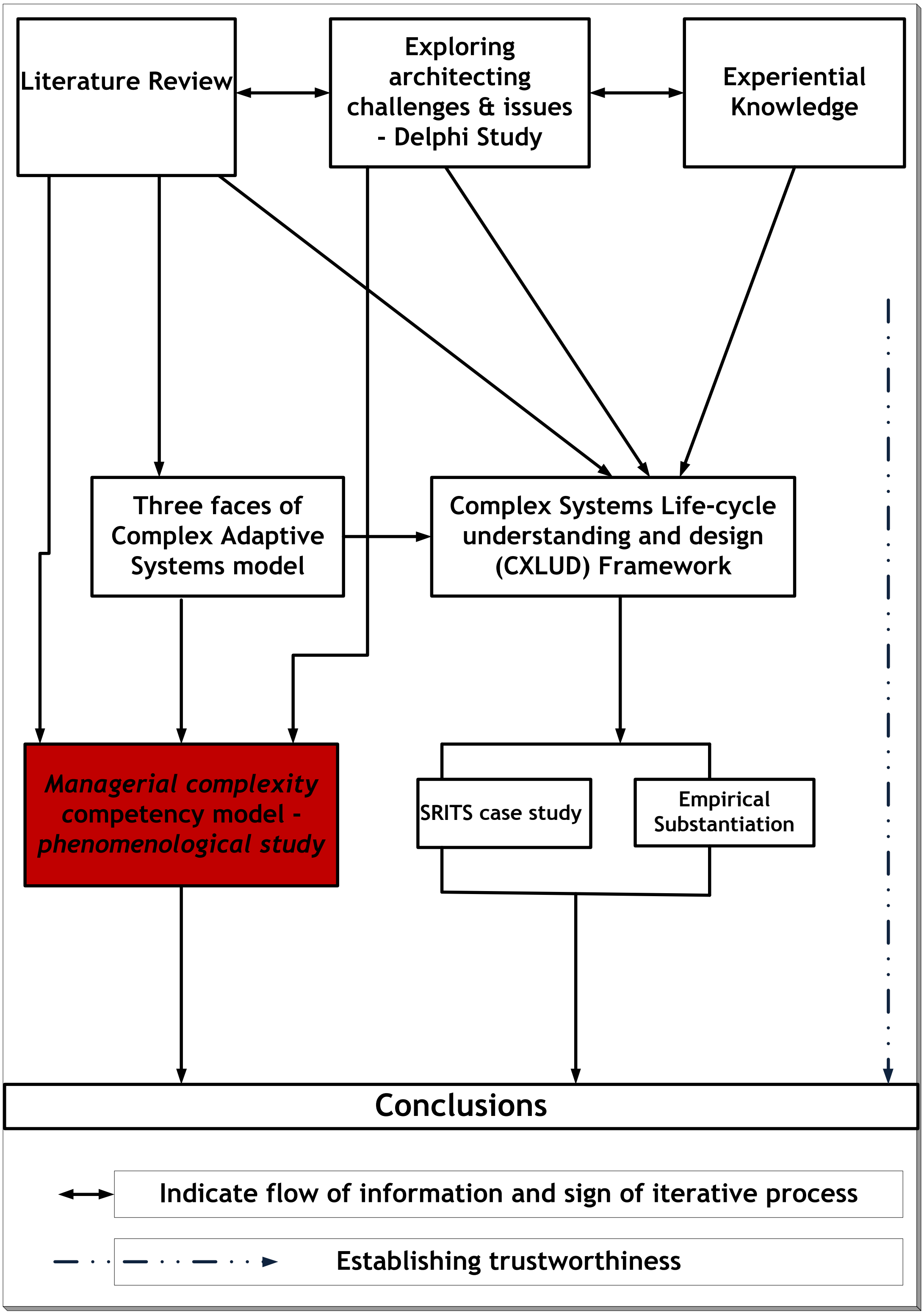

Figure 8-1: Research process with current stage highlighted

8.1 Developing managerial complexity competency model

In Chapter 3, a qualitative phenomenological research method was described as the preferred research design for the study presented in this chapter. The specific research outcome of this chapter is to provide empirical evidence for research question two and research objective seven (Section 1.3). The ability to undertake research on the development of a managerial complexity competency model requires an appropriate research landscape to promote trans-disciplinary domain inquiry. The field of phenomenology serves as a highly suitable landscape for this research. To achieve the proposed managerial complexity competency model, the constructs and enablers consist of three steps – as shown in Figure 8-2. These steps, with a brief description of purpose, are as follows:

1. Study the Managerial Complexity Decision-Making Job

The purpose is to determine which managerial competencies complex adaptive system design and development project leaders currently have and are applying in their managerial complexity decision-making. We have done this through a qualitative phenomenological study of the lived experiences of project leaders with management responsibilities. The primary aim of the research was to explore the nature of managerial complexity learning from a phenomenological viewpoint i.e., from the level of lived experience. Of particular importance was the desire to explore the role of complexity theory knowledge within the managerial complexity learning process. The study sought to comprehend how the nine participants felt they had responded to the challenges of managerial complexity. Competencies can come from educational offerings, work experiences and life experiences.

2. Compile a list of knowledge, skills and abilities needed for success

The aim is to map all of the identified themes from the phenomenological constructs to the three faces of complex adaptive systems model abstracted in Section 4.1. The aim is to find out if complexity principles which are basic knowledge required for understanding, designing and controlling complex systems can inform managerial complexity. By creating theoretical propositions that were deeply grounded in the experiences of the participants rather than detached, analytical abstractions, we ensure that the research remained authentic.

3. Use the collated information to build the competency model

The collated information is used to construct the managerial complexity competency model.

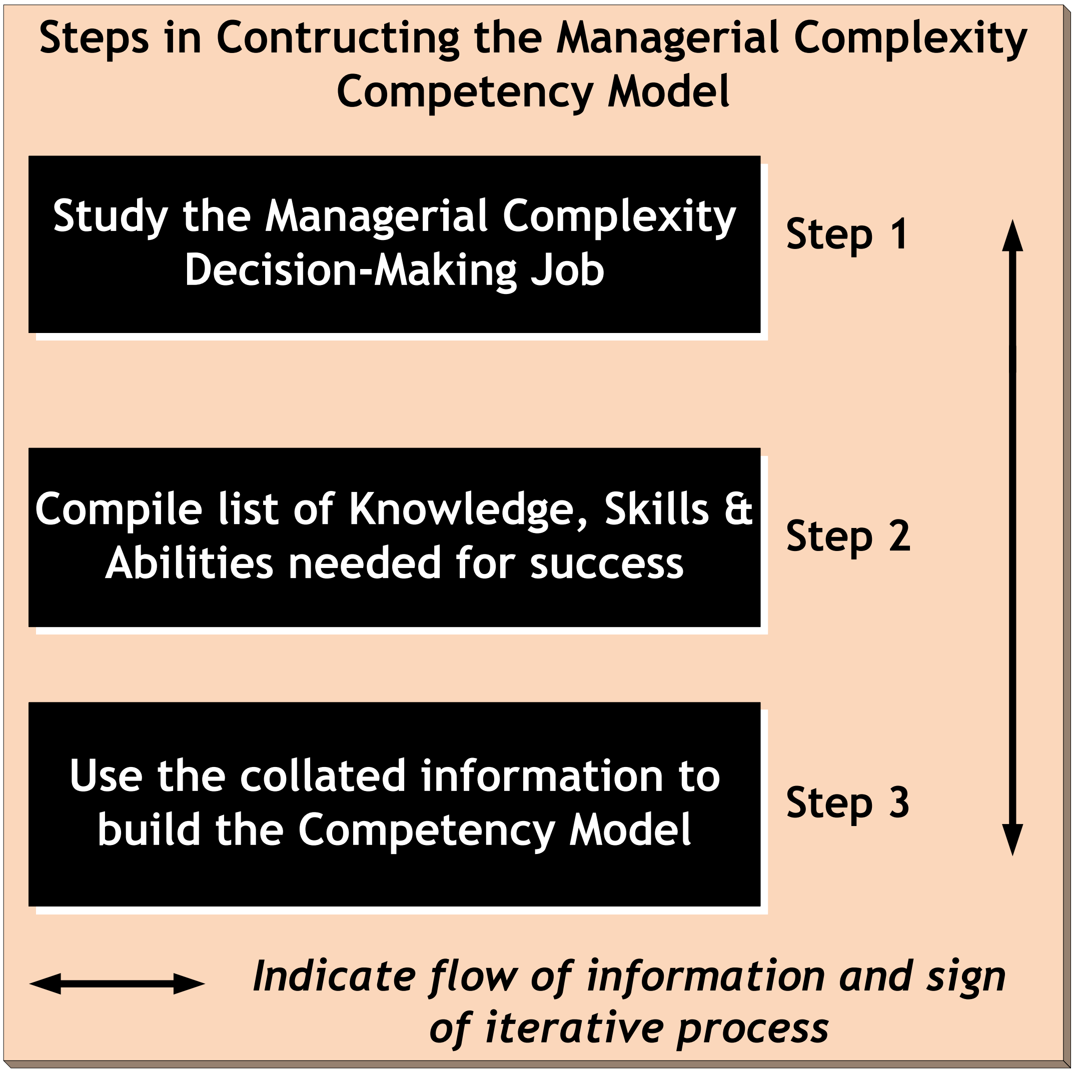

Figure 8-2: Managerial Complexity Competency Model Development Process Flowchart (Source: Author).

What follows are full details of the research work carried out and structured to reflect the three stated steps in Figure 8-2 above. Section 8.2 describes the Managerial Complexity Decision-Making Job analysis and discussion. Section 8.3 presents the list of knowledge, skills and abilities needed for success. Section 8.4 describes step 3 - Use the collated information to build the competency model. Finally Section 8.5 presents conclusions.

8.2 Presentation of Data and Results of Analysis

This section represents the results of the data analysis methodology and describes how the data supports the research question and objective. However, presentation of the participants' words describing how they experienced and managed managerial complexity as a complex adaptive systems project manager can be found in Appendix E.

8.2.1 Sample Demographics

A purposeful, criterion-based sampling method was used for this phenomenological study conducted with purposeful and homogenous participants drawn from a global IT consultancy. Each participant was over the age of 18 and volunteered to be part of the study. The sample included experts whose roles and responsibilities included research & development, requirements specification and operational risk management. Further, the participants were assured that all interview information would remain confidential and that their identity would be kept anonymous by following stringent data collection, storage and coding procedures. The participants were all involved with the SRITS project or generally working for LSW as defined in Chapter 6. Thus, for reasons of privacy and confidentiality, the names of the participants will not be disclosed and instead, WTN1 for interviewee 1, WTN2 for interviewee 2 and so on will be used. Basic demographic data for each participant is provided in Table 8-1.

The average number of years of project leadership experience was 5.6, with a range from 2 years to 10 years. The average number of years of complex adaptive systems project leadership experience was 2.9, with a range from 0.5 years to 6 years. Two of the participants had only what can be classified as complex adaptive systems project leadership experience, thus their totals were the same for both traditional systems engineering and complex adaptive systems project leadership experience. As a result, their lived experiences may have differed based on their level of particular systems experience.

Table 8-1: Phenomenological Study Participant Demographics (label PL denotes project leadership and CAS PL denote complex adaptive system project leadership)

Participant	Gender	Total PL (years)	CAS PL (years)	Location
WTN1	**M**	**8**	**3**	**UK**
WTN2	**M**	**2**	**2**	**UK**
WTN3	**M**	**6**	**5**	**India**
WTN4	**M**	**9**	**3.5**	**USA**
WTN5	**F**	**4**	**1.5**	**USA**
WTN6	**M**	**10**	**6**	**UK**
WTN7	**F**	**4**	**0.5**	**India**
WTN8	**F**	**2**	**2**	**India**
WTN9	**M**	**6**	**3**	**India**

8.2.2 Design of the Questionnaire

The researcher utilised the interview guide listed in Appendix E. The questionnaire consisted of the following parts:

- Demographic Questions.
- Experiences with decision-making with regard to managerial complexity issues in your development and management project.
- Indication of the overall project success.

The responses were rich with relevant data, yet several got off-topic. This was expected since the interview questions were unstructured.

8.2.3 Research Findings/Data Constitution

This section presents the process of data analysis and the findings of this qualitative research study. The process is fully described in Section 3.5.2 and Appendix E.

Step 1 - Listing and Preliminary Grouping

A horizontalization process was broadly applied to the participants' experiential descriptions to ensure a comprehensive listing of relevant statements and expressions were identified (i.e., analysed through the lens of complexity science —specifically, key principles of complex adaptive systems). Each relevant statement was assigned to a descriptive label in order to parse and categorise the data for further analysis. The aim was to discover strategies and practices that will form sets of skills, knowledge and abilities required of project managers for reduction of managerial complexity decision making challenges. After conducting the preliminary grouping process, 28 statements were identified and these statements represent non-repetitive significant statements.

Step – 2 Reduction and elimination

With the broad and generally defined horizons coded for each transcription, the reduction and elimination phase of the data analysis process was to determine invariant constituents. The invariant constituents are the unique and essential units of meaning that capture the textual qualities of the experience. This is what enabled the understanding of the participants' perspectives. Two tests in the form of reflective questions were applied to each of the 28 coded expressions from step 1 to extract the invariant constituents. The questions were:

1. Does it contain a moment of the experience that is a necessary and sufficient constituent for understanding it?
2. Is it possible to abstract and label it?

Expressions meeting both criteria were coded as the essential horizons of the experience. Otherwise, the expression was eliminated. At the end of the reduction and elimination procedure, 25 invariant constituents were extracted (Table 8-2). The 25 invariant constituents were coded as free nodes using exact descriptive terms designed to enhance step 3 (clustering and thematising) process.

Table 8-2: A summary of the invariant constituents

No	Invariant Constituents
1	This was my first project as a system development team manager where development team members are scattered around the globe.
2	Important to reduce lack of access and improve situational awareness.
3	Much of the project design and planning work undertaken through a multidisciplinary technical working group that was established early in the project has been shown to be particularly effective.
4	Whatever good that you build with one team member carries on to many, many more as each of you goes out and form new relationships.
5	Team members from designers to developers work side-by-side and have input during each stage of the analysis and construction processes.
6	What was helpful and has been very productive is establishment of simple rules that every member of the project team has to know about on joining the project.
7	What I notice on my first four months of taking up the job was that it can take lots of listening and interacting before you can move to that next level where you have a relationship with the team that is two-way.
8	We have people in New Delhi, USA, Europe all with different time zones.

9	At final analysis most of the issues and requirements making up the system and project environment are of different level of complexity.
10	Order is created in a system without explicit hierarchical direction.
11	People can and will process information, as well as react to changes in information.
12	Although expertise can contribute but is neither necessary nor sufficient to assure success.
13	It is therefore essential to recognize and acknowledge that every team member is unique and must be understood as an individual.
14	Confusion and uncertainty at first, then clarity.
15	You encourage and thank people for doing what they are actually paid to do.
16	We are always expecting the requirements to change before the end of each project and I always expect that I will lose one of the core team members at some point before the end of the development.
17	All my project team members have access to the company global knowledge management systems and we have regular brainstorming and ideation sessions.
18	Most require serious coordination, multiple perspectives and organised responses.
19	There are always different perspectives in most issues due to interacting together.
20	All opinions were valued.
21	Making an effort to understand the current capabilities and learn has been very helpful.
22	Helping others to experience what you have experienced so they can pass it on, basically resulting to an unintended consequences.
23	Every ideas/creativity was welcomed. I had to keep finding ways to influence and encourage the team.
24	Would have liked even more meetings/interactions/assignments.
25	Most often plans are developed at the lowest levels and are then passed on to each next higher level.

8.3 List of knowledge, skills and abilities needed for success

The aim of this section was achieved by clustering and thematizing the invariant constituents identified in Section 8.2.3. The invariant constituents were indexed against a pre-defined coding scheme based on consistent associations and contextual relationships. The coding scheme was developed based on complexity theory (Section 4.1). Some of the predefined coding adopted in this research, together with the definitions are shown in Table 4-1. However, this was expanded upon with codes that emerged during the analysis process. As the researcher considered the words used by the project leaders and conceptualisations of complex adaptive systems characteristics, the researcher employed imaginative variation as a phenomenological tool to expand understanding and appreciation of this step.

Overall, fourteen unique themes listed in Table 8-3 (see column Category - Theme Description) emerged during the clustering and thematizing procedure and each were identified as the core themes of the experience informed by complex adaptive system characteristics. The final analysis structure for the study is depicted in Table 8-3.The identified core themes (Category - Theme Description) are therefore the necessary complexity thinking knowledge, skills and abilities required for success in managerial complexities decision-making. In Table 8-3, the column marked Invariant Constituents is the mapping of the initial data in Table 8-2 to the appropriate core theme.

Table 8-3: Mapping of the Invariant Constituents to Core Themes

No	Category- Theme Description	Invariant Constituents
1	Adaptive	This was my first project as a system development team manager where development team member are scattered around the globe.
2	Simple rules	Important to reduce lack of access and improve situational awareness.
3	Self- organization	Much of the project design and planning work undertaken through a multidisciplinary technical working group that was established early in the project has been shown to be particularly effective.
4	Emergent	Whatever good that you build with one team member carries on to many, many more as each of you goes out and form new relationships.
5	Interaction	Team members from designers to developers work side-by-side and have input during each stage of the analysis and construction processes.

6	Learning	What was helpful and has been very productive is establishment of simple rules that every member of the project team has to know about on joining the project.
7	Anticipation	What I notice on my first four months of taking up the job was that it can take lots of listening and interacting before you can move to that next level where you have a relationship with the team that is two-way.
8	Co-evolution	We have people in New Delhi, USA, Europe all with different time zones.
9	Diversity	At final analysis most of the issues and requirements making up the system and project environment are of different level of complexity.
10	Unintended consequences	Order is created in a system without explicit hierarchical direction.
11	Collaboration/ Decentralized control	People can and will process information, as well as react to changes in information.
12	Adaptive	Although expertise can contribute it is neither necessary nor sufficient to assure success.
13	Simple rules	It is essential to recognize and acknowledge that every team member is unique and must be understood as an individual.
14	Open boundaries	Confusion and uncertainty at first, then clarity.
15	Emergent	You encourage and thank people for doing what they are actually paid to do.
16	Interaction	You encourage and thank people for doing what they are actually paid to do.
		We are always expecting the requirements to change before the end of each project and I always expect that I will lose one of the core team members at some point before the end of the development.
17	Learning	All my project team members have access to the company global knowledge management systems and we have regular brainstorming and ideation sessions.
18	Anticipation	Most require serious coordination, multiple perspectives and organised responses.
19	Co-evolution	There are always different perspectives in most issues due to interacting together.
20	Diversity	All opinions were valued.

	Adaptive	All opinions were valued.
21	Purposefulness	Making effort to understand the current capabilities and learn has been very helpful.
22	Flexibility	Helping others to experience what you have experienced so they can pass it on, basically resulting in an un-intended consequences.
23	Adaptive	Every ideas/creativity was welcomed. I had to keep finding ways to influence and encourage the team.
24	Simple rules	Would have liked even more meetings/interactions/assignments.
25	Self- organization	Most often plans are developed at the lowest levels and are then passed on to each next higher level.

From Table 8-3, we can see from the mapping that some quotes (i.e., Invariant Constituents) fit under more than one core theme, whereas others were specific to just one. This multiple mapping is not surprising as the principles are inter-dependent sub-theories or ideas that cannot be, nor should they be, easily separated. This observation, in itself, is an indication of complexity - principles are interdependent with actions. Samples of the “Individual Textual Description” can be seen in Appendix E. Based on the individual textual descriptions, a description of the participant’s experience is created that attempts to depict the underlying reasons for the experience and identifies the thoughts and feelings associated with the experience.

8.4 Constructing the Competency Model

The purpose of this section is the construction of a managerial complexity competency model informed by complexity science sub-theories. In Section 8.3, we identified the decision-making lived experiences of the project leaders and mapped them to appropriate competencies. The research findings indicate that, the competency of project managers for successes in managerial complexity mainly included fourteen competency indicators from a complex adaptive system thinking perspective.

Managerial complexity competence in this thesis is concerned with practitioners, their development and how they make skilled complexity engineering contributions to meet society’s demanding needs for complex adaptive systems and services. When there is a considerable field of knowledge and a broad body of literature about a specific topic such as we have in complexity science, one way to make a contribution to knowledge is to propose a framework for reviewing that knowledge. The ‘three faces of complex adaptive systems conceptual model’ derived in Chapter 4 (Section 4-1) is the natural candidate for the complex adaptive systems methods of practice. Accordingly, it is employed here as the basis for developing a managerial complexity competency framework. The value of this approach lies in its adoption of a widely accepted model of design processes. The three levels in the ‘three faces of complex adaptive systems conceptual model’ were taken to represent the highest level in the competency model. The proposed managerial complexity competency model will include three levels defined as follows:

1. Categories of like competencies,
2. The competencies, and
3. Behaviourally-based definitions for each competency.

In these, the *Categories of like competencies* equal the *three levels of complex adaptive system* (i.e. Understanding, Perception and Action Taken); the *Competencies* equal the *Core Themes* identified in Section 8.3 (Table 8-3); and finally the *Behaviourally-based definitions for each competency* equal the *meanings attached to each core theme*. Data was incorporated into the categories of like competencies using researcher judgment on how suggestions were in alignment.

By organising the findings in this heuristic way, we hope to provide a conceptual model that makes it easier for the readers to understand the lived experience of the project leaders in managerial complexity challenges and how complex systems principles can inform the understanding, perception and action taken. To identify this patterned competency model, we will label it the “Understanding, Perception and Action Taken” Model (UPA) - a phenomenological derived managerial complexity competency model for project leaders. A summary of the discussion including 1) categories of competencies, 2) the competencies themselves, and 3) behaviourally-based definitions for each competency forming the UPA model is illustrated in Figure 8-3. The ultimate goal of the use of the Competency Model is to better understand what might constitute an appropriate organizational response to managerial complexity decision making.

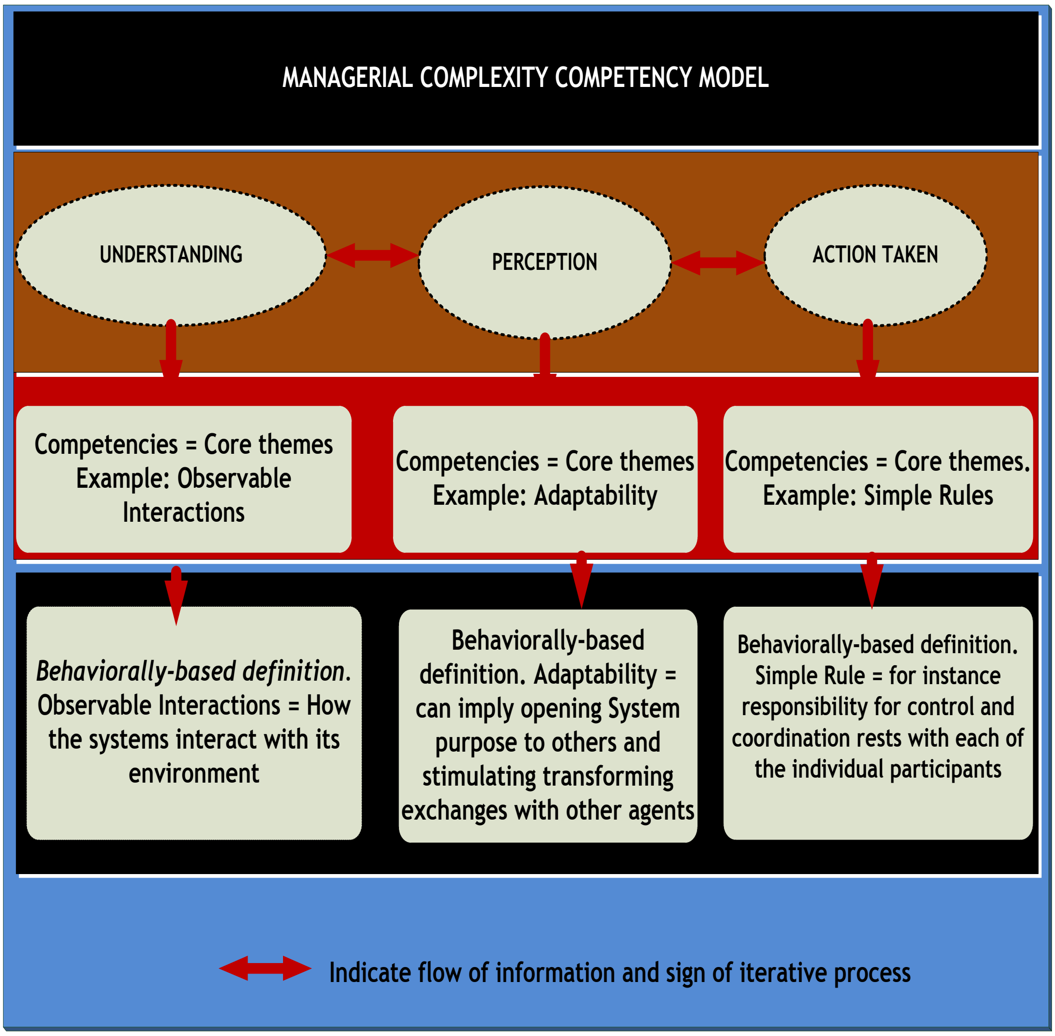

Figure 8-3: UPA – Managerial Complexity Competency Model (Source: Author)

With this understanding comes the possibility of influencing practice. Competence is seen as the relevant qualities that enable individuals (and teams) to beneficially employ a set of processes to change events and outcomes. Expressing the competence model (Figure 8-3) proposed is, at its most abstract, shown in Figure 8-4. It advances that managerial complexity competence is the developed ability of project leaders to control complex adaptive systems life cycle processes in order to achieve beneficial change and/or interventions.

Each of these characteristics is worth thinking about because the less your organisation has of these, the less healthy the managerial complexity techniques will be, and the less likely the organisation will thrive, or even survive in these rapidly changing times.

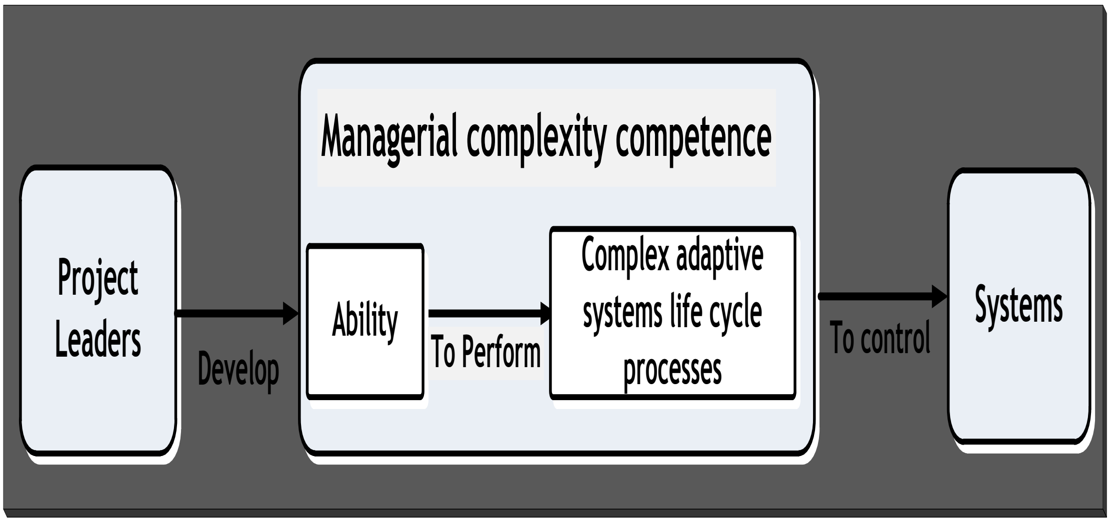

Figure 8-4: Project leaders Control of Complex Adaptive Systems using Managerial Complexity Competence (Source - Author)

The core of this approach to representing managerial complexity competence is the formulation of a model that defines the major categories of project leader ability required to control complex adaptive systems life cycle processes. Competence in project complexity and many other pursuits is a function of several factors or variables and this can result to diversity of models. In this thesis, the research has focused on two strongly interrelated components, namely, knowledge and experience. The way these relate to project leader ability and hence to competence are shown in Figure 8-5.

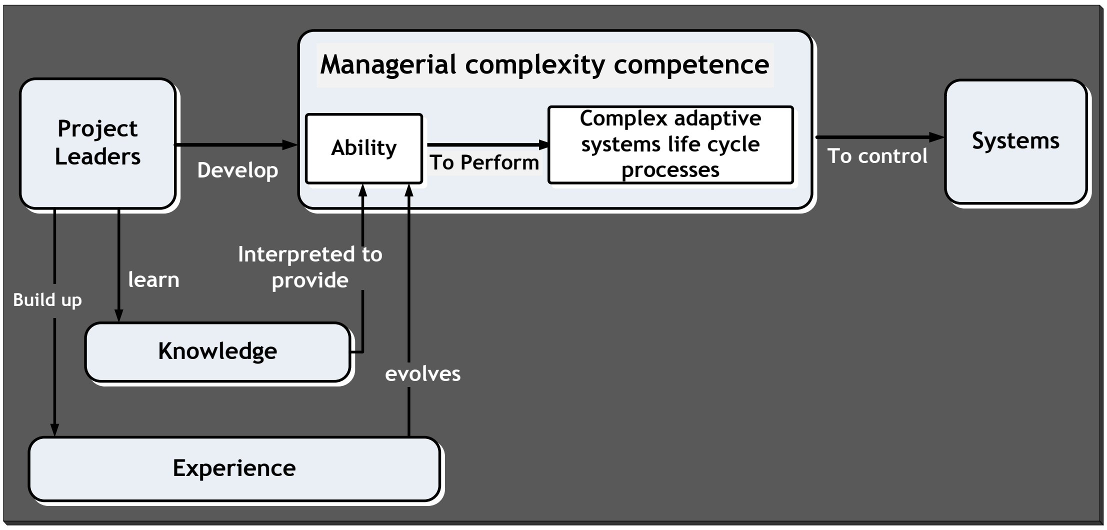

Figure 8- 5: Focus of the UPA Managerial Complexity Competence Model (Source - Author)

Figure 8-5 illustrates how complex adaptive systems ability of a project leader or a team relates to:

1. Knowledge: the information gathered from others, often in the form of academic teaching, formal tutelage or the assimilation of a recognised body of knowledge that is concerned with schooling in complex adaptive systems design and management;
2. Experience: the direct personal participation in the practicality of systems control through which the project leader can benefit from the judgment, wisdom and mentored of others *in situ*.
3. For the project leader, for an organization to grow in managerial complexity capability when implementing the complex adaptive systems life cycle processes, individuals within that organisation must build up the experience which will ultimately evolves into relevant ability and learn required knowledge whose interpretation led to ability to control the systems of interest.

In the next section, we discuss at a further detail selected behavioural attributes based on the phenomenological data using the three categories of ‘Understanding’, ‘Perception’ and ‘Action Taken’ as the building block.

8.4.1 Understanding and Managerial Complexity

This view specifies the competencies required to understand the context of the complex adaptive system and to develop and implement a strategy to deliver for instance, the emergent outcomes. The key elements of competencies (i.e. knowledge and experience) identified from the phenomenological data under the ‘Understanding Competency’ category include**:**

- Team autonomy - Developers in a complex adaptive systems development team require a degree of autonomy, e.g., they decide which use cases they are best fitted to implementing;

Appendix E (see Table E-1) contains more information on the phenomenological data.

8.4.2 Perception and Managerial Complexity

The category relate to the components of systems complexity thinking which enables the project managers to adapt to the demands of complex systems development process environment. The key elements of competencies (i.e. knowledge and experience) identified from the phenomenological data under the ‘Perception Competency’ category include**:**

- Co-evolution - The co-evolutionary process requires continuous knowledge sharing of managers and developers (developers need to understand the constantly changing business setting and managers the capability of new technology).

Appendix E (see Table E-2) contains more information on the phenomenological data.

8.4.3 Action Taken and Managerial Complexity

The category pertained to the key components of systems complexity thinking which describe the approach the project managers took to solving complex problems. The key elements of competencies (i.e., knowledge and experience) identified from the phenomenological data under the ‘Action Taken Competency’ category include**:**

- Self-organising - Managers do not plan and control in a rigid way. Managers must foster a context that allows the project to evolve and co-evolve to the edge of chaos where innovation and creativity are encouraged and emergence of new structures and forms is possible. The actions of the project managers can be called self-organising since the overall performance is given by the local rules followed by each team member, their local interactions generate global project patterns that cannot be reduced to individual behaviours.

Appendix E (see Table E-3) contains more information on the phenomenological study data.

8.5 Chapter Summary

This chapter reported on an investigation into project leaders' lived experiences of managerial complexity. Based on a phenomenological study, elements of the key competencies required of the project leader for managerial complexity success were identified and classified under managerial complexity competency model.

The practical implications of the research produced include the ability to describe managerial complexity in a manner consistent with the actuality of the lived project environment. In addition, the study shows that effective competencies can be developed. From the successes enjoyed by the project leaders in the projects, it is right to assume and conclude the science of complex adaptive systems, provide important concepts and tools for responding to the challenges of uncertainties in project management this century and beyond.

Thus, the implication for leaders and learning organisations is that complexity theory can be a powerful tool for overcoming ill-structured problems and learning through adaptation to achieve success. If and when leaders can look at complexity sciences as a way of being proactive, understanding the environment, learning from it and then adapting to those new emergent situations with novel ideas, they will be able to work around the problems they are facing. From a practical perspective, the findings provide a framework to challenge the existing dominant paradigms—accepted practices and bodies of knowledge in linking theory to practice.

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CHAPTER 9 CONCLUSIONS

Decisions made in the early phases of complex adaptive system development have a great impact on all subsequent stages of the design and management processes. It is therefore crucial to place pronounced emphasis on conceptual planning and the design specification. This thesis is concerned with the anticipatory capacity of system engineering organisation early phases in system development from a methodological standpoint, as well as with the early phases of project leaders' managerial complexity experience. To conclude, this thesis' contributions can be seen on a theoretical, empirical, as well as methodological level.

A sound system design framework will support engineering organisations by providing a context for decision-making and help organisations develop capabilities needed for the future.

This chapter summarises the research conclusions and presents future research directions and thus addresses the final research objectives introduced in Section 1.3. It starts by summarising the research along with its findings. This summary is organised based on the research chapters showing the main theme and rationale of each. Thereafter, the research contributions are discussed. Next, significant future research avenues that provide further development to this area of research are suggested. The relationship of this chapter to the preceding chapters of the thesis is presented in Figure 9-1.

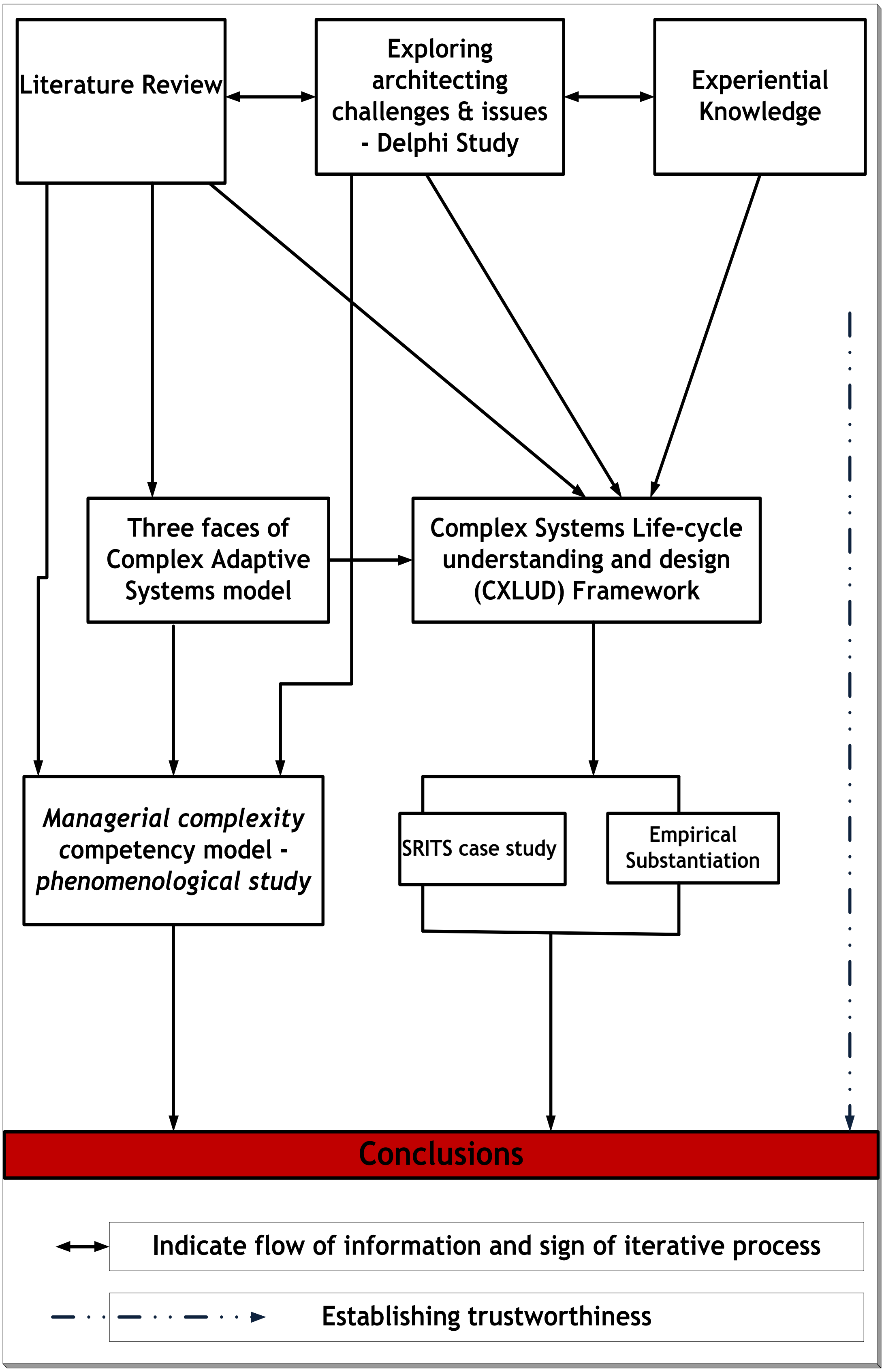

Figure 9-1: Research process with current stage highlighted

9.1 Research Overview and Findings

The research presented in this thesis aimed at enhancing anticipatory capacity of complex systems engineering organisations by proposing a new conceptual design methods and managerial complexity competency models. The thesis was organised into nine chapters.

Chapter 1 was the starting point of this thesis in which the author first explored the main motivation for conducting this research. The chapter presented a summarized overview of the research objectives, questions, methods, and findings. The introduction set the context of the study and the chapters that follow represented the process and outcomes of the research work. After establishing the research context, chapter one presented the research aim along with its objectives.

In Chapter 2, the research was put in context by discussing the related research domains showing (1) design methodology (2) design theory (3) process knowledge (4) complexity science and (5) system architectures research. These are relevant and important areas as theoretical background. Generally, the systems literature defines a system as a collection of components or parts that are organised (i.e., connected to each other) around a common purpose or goal. The Complex Adaptive System perspective would suggest that there are no grand theories which can explain complex system goals. Rather, Complex Adaptive Systems offer a ground up, component based, constructive templates for gaining insights and understanding.

In Chapter 3, the research design and the approach undertaken in order to solve the research problem and achieve its objectives were described. At the beginning of Chapter 3, the author classified information systems research paradigms into four categories: positivism, pragmatism, interpretivism (constructivism), critical theory, and objectivism. Given the nature of the research problem, processes and the type of output it produced, it was argued that the research fits the constructivism and pragmatism paradigm more than the other identified paradigms. Next, we discussed the reasoning and processes that would lead to the gathering of the knowledge base needed for construction of the artifacts and models.

In Chapter 4, an exploratory Delphi study on challenges and issues in system architecting was provided. The results of this exploratory study are two-fold: a set of specific architecting challenges and issues facing the architecting organization as well as actionable mitigations as perceived by the study participants are described. This worked-through

Delphi study is intended as problem identification for the proposed systems architecting and complex systems design framework developed.

Chapter 5 then introduced another main contribution of this thesis: CXLUD framework. CXLUD is a conceptual design methodology. CXLUD can be decomposed at a high level to three phases: 1) Design Innovation Control, 2) System Lifecycle Control, and 3) Architecture Realization Control. The process began by eliciting the real system needs and preferences and proceeds to selecting attributes and design variables under consideration. The conceptual design methodology facilitated the discussion of possible changes in the tradespace due to changes in needs or context.

Chapter 6 presented a case study of application of the CXLUD framework. In the case study the CXLUD framework as a conceptual design methodology is applied to a systems architecting of a “Financial Systemic Risks Infrastructure System (SRITS)” at one of the largest financial institutions in the United Kingdom. The case study is based on real architecting problems being faced by LSW at the time of writing of this thesis. Evolvability and adaptability were explored as an effective system attributes that can facilitate the ability of SRITS architecture to be modified across generations in the presence of changing contexts, or needs, allowing for the potential for the SRITS to deliver sustained value.

Chapter 7 presents a validation case study that has been developed to evaluate the effectiveness and understandability of the CXLUD Framework by potential users. An exploratory questionnaire was used to gather information empirically from experienced system engineers, designers, analysts and project managers.

Chapter 8 investigated development of phenomenological model. The purpose of this study was to understand the in-depth experiences of project leaders in complex adaptive systems environments to gain their understanding, perception and approaches to complex problems solving through their rich, thick descriptions. Interpretive and phenomenological methods were combined in this study through a series of written interviews designed to allow the research participants to reflect on and construct meaning based on their own decision-making experiences.

9.2 Guiding Research Questions and Objectives

There were two questions that the research sought to answer, introduced in Chapter 1.

1. Research Question 1 - What is the best way to package a design method and process that can demonstrably stimulate creativity and enable engineering of complex systems (architecture) in a heterogeneous, uncertain and changing context?
2. Research Question 2 - What are the relationships between complexity theories and project managers' perceptions of managerial complexity?

9.2.1 Accomplishments of Research Question 1

This question is explicitly addressed in Chapter 5 where a methodology to design and control complex adaptive systems is presented. This research aims to come up with a methodological framework, development and creation of design support environments for complex adaptive systems. The proposed methodology is named CXLUD framework. The ideas of CXLUD definitions have their roots in current practices and methods available in the literature. In that regard, the stages and steps described in CXLUD cannot be said to be novel. Still, the aim of this work is not for novelty but for synthesis.

The overall structure of the design methods and processes, summarised in Figure 9-2, is a logical and systemic conceptual framework which demonstrably stimulates creativity and enables conceptual design of complex adaptive systems in a heterogeneous, uncertain and changing context. The conceptual framework allows the description of any engineered complex adaptive systems as a collection of agents, where the goals of the adaptive system are determined by the purpose set by the designer.

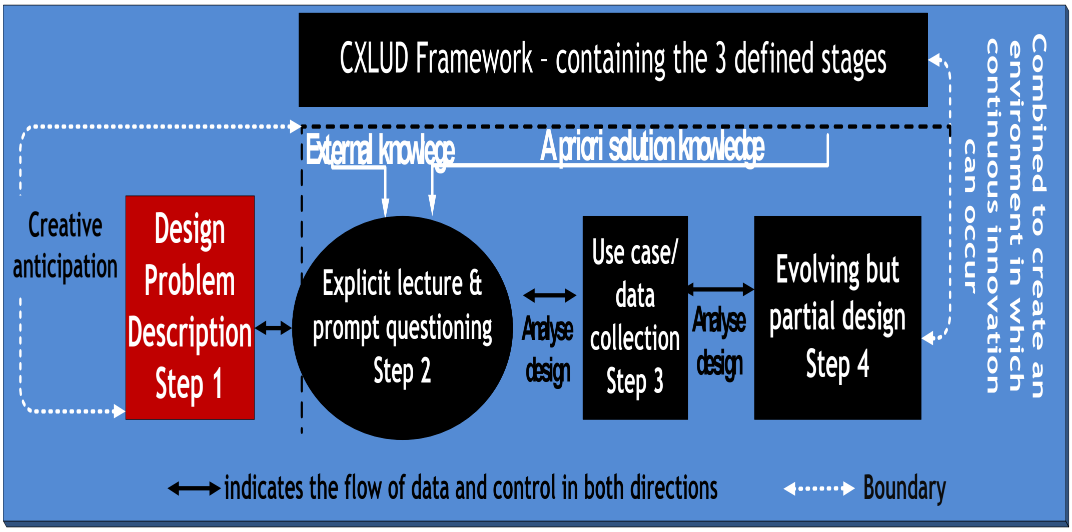

Figure 9-2: The overall structure of the development environment

The CXLUD framework proposes to use as an evolutionary design concept generation mechanism the concept of creative anticipation. The explicit lecture and prompting mechanism provided by creative anticipation is crafted to stimulate required design principle generation by providing some level of direction, without being completely directive as to impose answers to the design and control agents. The CXLUD Framework therefore represents a design environment in which a process of innovation and creative change can take place facilitated by the creative anticipation. Different ways in which this can be done were identified, to facilitate the design and implementation of temporal system properties or ilities that will steer the complex adaptive system through a dynamic problem domain.

Another attribute of the framework is implicit usage as a communication pathway among designers and stakeholders. The issue of effective and efficient communication pathway is central to the design process. Though not necessarily explicitly addressed in this thesis, communication is both the enabler and barrier to the creation of valuable system designs and management of the complexity. Communication is the relay of information from the originator of the need to the solver of the need and enables collaboration within projects. With the Creative Anticipation design procedure, the involvement of all the relevant project stakeholders in the design process cuts through barriers such as differing expectations. When collaborating, process clarity and information consistency result in little rework and positive iteration enables consideration of multi-disciplinary design trends inherent in complex adaptive systems.

Another attribute of the framework is its simplistic representation. Conceptually, the various constituents of the framework are straightforward to understand and discuss. One benefit of breaking down a potentially complex situation into simple ‘stages’ and ‘steps’ and information flows is that it can facilitate the framework development, learning and subsequent application.

In order to evaluate the applicability of the CXLUD framework, a case study was employed; the case study and key findings are summarized in Chapter 6 and supplemental material provided in Appendix C and the findings form one contribution of this thesis. As of the time of the completion of allotted case study time, the case application development is still ongoing, so it difficult to measure the CXLUD framework potential impact. Nevertheless, a key conclusion on the validity of the creative anticipation based on the case study experience is that researchers espousing an explicit lecture and a directive prompting mechanism design procedure should be careful to select the appropriate amount of direction to stimulate creativity. This is based very much on the design participants. Thus, the level of direction should consider the possibility that some designers may be more creative by modifying existing solutions, while others are better at creating entirely new solutions from scratch.

CXLUD was judged to be conducive to studying system's architecture, as it is enhanced by a set of qualitative constructs for answering questions about the reasons (*why*) and process (*how*) of change. The overall generality of the result, however, is limited, as the framework has only been applied to one system development case. However, the acceptance of the constituents and processes among experienced system designers and managers involved in the empirical substantiation study, as well as by the research community through the acceptance of the presented research papers, indicate a wider applicability.

The main limitation of the CXLUD framework is its generality, since it can be applied to any domain. It is also its main virtue. While the CXLUD framework approach is low-cost, logical and based on sound theory, it demands more subjective inputs about the value judgments of system designers and it is time consuming in setting up the process.

9.2.2 Accomplishments of the Research Questions 2

The question demands an investigation into the relevance of complex adaptive systems characteristics for implementation processes and relates the findings to project managers' perceptions of managerial complexity. We can conclude here that complexity science provides a useful framework for understanding the open-ended, unpredictable and innovative managerial complexity reduction process analyzed in this thesis. It also offers helpful practical guidelines for future managerial complexity learning activity and curriculum development. The final outcome of the research is managerial complexity competency model, which will allow the assessment of individual and organizational responses to it in the future.

There were three aspects of research involved in achieving the research question aims. First, based on a literature-based exploratory study, elements of "what makes a system complex adaptive" were identified and classified under the dimensions of understanding, perception, action taken - the three faces of complex adaptive system model. These dimensions reflect the fundamental drive of design. This provides a framework for the description of the level of managerial complexity challenge or difficulty. The second source of data was from the project managers themselves. Based on a multistage qualitative, phenomenological study, meaning and nature of project manager's direct managerial complexity experiences through their first person accounts were identified.

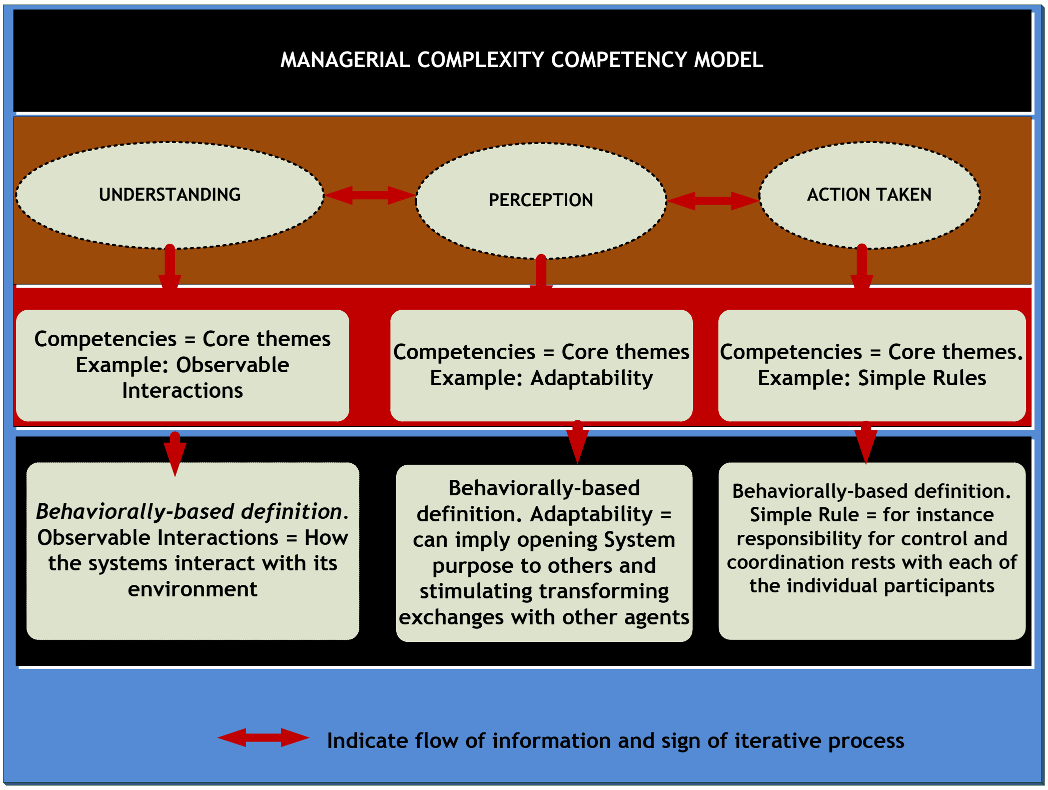

Figure 9-3: UPA – Managerial Complexity Competency Model (Source: Author)

The proposed managerial complexity competency model has three main phases including understanding, perception, and action taken (Figure 9-3). We can conclude that the UPA – Managerial Complexity Competency Model is a complex adaptive system which provides a decomposition of managerial complexity goals on sub-goals and description of relations between them. Thus, implementing the model is a three step process.

9.2.3 Accomplishments of the Research Objectives

Each of the main chapters in this thesis outlines one of the eight primary research objectives (see Section 1.3) of this thesis. What follows in Table 9-1 is a summary of shows how these research objectives have been answered and achieved.

Table 9-1: Accomplishments of the Research Objectives

Research Objectives	Accomplishments
1. To explain the research	This objective was achieved in Chapter 3. The nature

	paradigm, methods and techniques that fit the current research questions and led to the final artifacts developed in this research.	of the research problems made it suitable to use a qualitative research approach as well as a constructive approach. Chapter 3 distills the core principles of a Delphi, Case Study and phenomenological research designs and, by means of a specific study, illustrates the methodologies presented in Chapters 4, 6/7 and 8 respectively. The decisions to adopt a qualitative approach to the research through the use of a Case study, Delphi and Phenomenological studies has been discussed and justified.
2.	To explore and develop a conceptual framework to describe the patterns that enable a better understanding and analysis of what is complex adaptive systems.	We accomplished the second objective in Chapter 4 as we provided three faces of complex adaptive systems framework based on design activities concept given that it is the main background theory for the current research. It is well known in the complexity engineering community that architectural patterns (including hierarchies and abstraction layers) should be used in design because they play an important role in controlling complexity. These patterns make a system easier to evolve and keep its separate portions within the bounds of human understanding so that distributed teams can operate independently while jointly fashioning a coherent whole.
3.	To undertake a study to explore, describe and explain systems architecting challenges and issues facing a complex systems architecting design team and secondly, given the research need for enhancing anticipatory capacity of the architecting organisation utilise the findings to suggest a competency model.	We accomplished the third objective in Chapter 4 as we provided system architecting practitioners validated list of challenges and issues. Using the validated challenges and issues, a conceptual model (named the CIRD model) capable of organizing system architecting challenges and issues was proposed. The validated list is also a contribution to study of sources of complexities in complex systems architecting and the CIRD Model is a foundation for future research aimed at developing competency model.

4.	Undertake a study to constructively create an organised design construct and enabling environment which stimulates creativity and innovation when bringing desired properties into system conceptual design.	The objective was achieved in Chapter 5 where we discussed the development of CXLUD framework. The use of creative anticipation design procedure was proposed as one method of ensuring creativity and innovation. Using creative anticipation procedure to capture key decision maker's design preferences is seen as a method for ensuring the delivery of value, since these preferences captured will reflect the possible way by which the decision maker will decide if the solution is worthwhile. Positive reception, both by practitioners of the framework and academia representatives at conferences added support to the framework.
5.	Evaluate and validate objective 4 through real-life cases in regards to financial systemic risks infrastructure systems.	The objective was accomplished in two Chapters. First, in Chapter 6, we utilised the CXLUD framework to examine bringing value robustness design principles into the financial systemic risks infrastructure systems (SRITS) system architecture conceptual design case study. The system engineers, designers and project manager involved in the case application emphasized that the application of the creative anticipation ideation mechanism and structured stages and steps as defined in the CXLUD specification had a positive impact on the understanding of architecting value robustness enablers into the case application.
		In Chapter 7, a study with practicing system engineers and managers served to ground the theory-based CXLUD framework research to 'state-of-the-practice' was carried out. We presented the framework to complex adaptive systems design community and elicited responses through an exploratory questionnaire to assess the practicality, necessity, understandability, completeness and effectiveness of the framework.
6.	Undertake a study to explore how project leaders perceive and	We achieved this objective in Chapter 8where we identified possible value drivers capable of overcoming challenges related to managerial complexities. The

describe the lived experiences of coping with managerial complexity	drivers identified were derived from project leaders' lived experiences, judgment and decision-making from descriptive, normative, and prescriptive points of view.

9.3 Research General Contributions

The clearest contribution this research makes to practice is the rich knowledge and insights it supplies to practitioners concerned with complex adaptive systems architecting and design.

The key contributions (also listed in Section 1.5) can be summarized as (a) the development of a three faces of complex adaptive systems (point 1 in Figure 9-4); (b) the development of conceptual model of the architecting challenges and issues (point 2 in Figure 9-4); (c) the development of a framework (i.e., design process and design procedure) for complex adaptive systems conceptual design (point 3 in Figure 9-4); and (d) the development of phenomenological model (point 4 in Figure 9-4).

1. Conceptualization of complexity sciences characteristics into three abstraction level consisting of understanding, perception and action taken. The resultant conceptual framework proved useful in constructing managerial complexity competency model.
2. Identification and definition of a CIRD conceptual model representing architectural challenges and issues facing complex systems architecting organisation.
3. Developing a conceptual framework known as Complex Systems Lifecycle Understanding and Design (CXLUD) as a design method capable of supporting and stimulating creativity and environment where innovation can occur.
4. Phenomenological derived Understanding – Perception - Action Taken {UPA} Managerial Complexity Competency Model conceptualized to inform how complex systems science can inform managerial complexity challenges in complex adaptive development environment.

Figure 9-4: Contributions of the Current Research to Theory

9.4 Potential for further Research

This thesis opens the door to many exciting research opportunities. There is much room for the framework to mature and grow through further research. The following points are some possible areas for development of the CXLUD framework and UPA managerial complexity competency model. Although the feedback obtained from the members of the systems architecting community and single case application regarding the CXLUD Framework leads to the substantiation of the framework, conducting a longitudinal study using the CXLUD Framework would provide opportunities for contribution as well. Another opportunity lies in investigating the automation of the portions of the framework. Therefore future work may also include developing tools to automate the pre-adoption assessment process and assist with evaluation of the results. Another opportunity lies in developing self-contained tutorial that leads complex systems architects and designers to use CXLUD conceptual framework as a reasoning tool for new recruits. A proposed future study is using a quantitative descriptive approach to determine whether or not a relationship exists between successful project outcomes and UPA managerial complexity competency model.

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APPENDICES

This section includes appendices which provide supplementary information that was not presented in the main body of the thesis. There are four appendices:

- Appendix A provides glossary of selected terms.
- Appendix B provides supplemental material for Delphi Study.
- Appendix C provides supplemental material for SRITS Case Study.
- Appendix D provides supplemental material for Empirical Validation Case Study.
- Appendix E provides supplemental material for managerial complexity competency model phenomenological study.

Appendix A Glossary of Terms

Agent

An agent is a description of an entity that acts on its environment (Greshenson, 2007).

Anticipatory capacity

Anticipatory capacity is the capacity of an organization to continuously develop and apply knowledge acquired through a structured approach to anticipate changing scenarios as needs and context change over time (Rhodes and Ross, 2009).

Conceptual Design

Conceptual Design is the phase during development in which “the needs of the target market are identified, alternative product concepts are generated and evaluated, and one or more concepts are selected for further development and testing.

Conceptual design is one phase within the design process, before detailed design but following the development of requirements.

Complexity

1. In systems engineering and systems theory, definitions classify complexity into two main categories: structural complexity concerning the complicatedness of the order of the elements in the system and behavioral complexity regarding the behavior of the system over time (Sussman, 2003).

Complex adaptive systems

1. Complex adaptive systems are composed of independent (or conditionally independent) agents whose behavior can be described as based on physical, psychological, or social rules, rather than being completely dictated by the dynamics of the system. Overall system structure and behaviour inherently changes over time. The behaviours of complex adaptive systems usually can be influenced more than they can be controlled (Rouse and Serban, 2011).
2. Understanding the agents or stakeholders in the system in terms of goals, objectives, strategies, tactics and plans can enable designing incentives and inhibitions that may lead to tipping points (Gladwell, 2002).
3. Complex Adaptive System refers to a field of study and resultant conceptual framework for natural and artificial systems that defy reductionist (top-down) investigation. Such

systems are generally defined as being composed of populations of adaptive agents whose interactions result in complex non-linear dynamics, the results of which are emergent system phenomena (Brownlee, 2007).

Characteristics of complex adaptive systems

Complex adaptive systems are perhaps best defined based on their characteristics. Table 1 lists and describes some commonly accepted features of complex systems. A list of some commonly accepted features of complex adaptive systems (Manson, 2001; Johnson, 2010; Brodu, 2009; Heylighen, 2008).

Feature	**Description**
System is open	Complex systems exist in a thermodynamic gradient, dissipate energy and are typically far from an energetic equilibrium, but despite this they may show local dynamically stable patterns or phenomena.
System boundaries	It is difficult to define or locate the boundaries of a complex system and it may require relatively arbitrary decisions by the observer. Complex systems are often nested and this may lead to difficulties in defining the boundaries Components of complex may themselves exhibit complex characteristics.
Interactions between objects	Interactions between many linked objects or agents lead to a network that can share information. The rules of interaction are important and can lead to phenomena such as system memory and emergent behaviour.
Feedback	Feedback happens when part of an output signal from a system is passed as an input to the system, affecting the dynamic behaviour of the system and modifying elements or components of the system.
Emergence	Emergent phenomena arise out of nonlinear behaviour and simple interactions between numerous agents or objects.
Interaction	The separate parts of a complex system influence one another constantly.
Nonlinear behaviour and relationships	For a complex system it is not possible to write a linear sum of independent components to solve for a nonlinear variable. Complex nonlinear systems are inherently unpredictable in that they have the characteristic that small perturbations in the system may cause large

	effects, a proportional effect or no effect at all.
The system is dynamic	Complex systems constantly change through the process of self-organisation, the property that allows systems to change their internal structure to more effectively interact with their environment. Some complex systems evolve towards a dynamically stable condition known as self-organised criticality with features.
Memory and learning	Regularly occurring external relationships reinforce the growth of the same set of components and sub-systems in a complex system. This reinforcement can cause the system to appear to have a memory through the persistence of internal structures.
interdependence	Everything is related and interdependent. Affecting one part of the environment will affect all parts of the environment. The ecosystem hangs in a balance, and if we disrupt one part of the balance, we can throw the whole system out of whack.

Competency

1. A cluster of related knowledge, attitudes, skills, and other personal characteristics that affects a major part of one's job (i.e., one or more key roles or responsibilities), correlates with performance on the job, can be measured against well-accepted standards, and can be improved by means of training and development (PMI, 2007, p. 73).
2. Is finding the key ability to enhance their performance development from the high-performance workers. Therefore, competency means the individual’s characteristics such as knowledge, skills and ability, which are sufficient to affect the individual's ability to generate excellent performance (Fang et al., 2010).

Competency model

1. A competency model is an organizing framework that lists the competencies required for effective performance in a specific job, job family (i.e., group of related jobs), organization, function, or process.
2. Individual competencies are organized into competency models to enable people in an organization or profession to understand, discuss, and apply the competencies to workforce performance.

3. The competencies in a model may be organized in a variety of formats. No one approach is inherently best. Rather, organizational needs will determine the optimal framework. A common approach is to identify several ‘‘core’’ or ‘‘key’’ competencies that are essential for all employees, and then identify several additional categories of competencies that apply only to specific subgroups.

Design

1. Design for value robustness is an approach used to search for design options that will continue to perform well in the face of changing operational environments and a dynamic context (Ross, 2006).

Framework

1. Frameworks help us organize how we think and communicate about complex or ambiguous concepts. If an organisation employs a framework, the people can more easily achieve clarity of thought and purpose. In a nutshell, a framework can also help us succeed in realising value from program and efforts and data.
2. The Oxford English Dictionary (2004) defines a framework as a structure composed of parts framed together, especially one designed for enclosing or supporting something.
3. Boar (1999) defines an architecture framework as an environment for developing architectures or implementations of systems

Imaginative variation

Moustakas described this process as the application of imagination to understand the how and why of the experience (Moustakas, 1994).

Model

1. A model is an abstraction of a system, aimed at understanding, communicating, explaining or designing aspects of interest of that system (Dori, 2002).
2. A model presents a view of the system. A view is defined as a representation of a system from the perspective or related concerns or issues (Maier and Rechtin, 2009).
3. Models can be textual or visual representations of the system based on the context the model is being built for. Models are a possible way to project the system through highlighting different aspects of it.

Perturbation

Mekdeci et al., (2012) defines a perturbationas any "unintended state change in a system's form, operations, or context which could jeopardize value delivery." This definition should also include any change in needs of the system as well.

Phenomenological reduction

As described by Moustakas (1994), phenomenological reduction is a process that textually describes the object (in this case, managerial complexity), reflects on the participant descriptions of the phenomena, and refines the descriptions.

Purposive sampling

Purposive sampling, also known as judgmental, selective or subjective sampling, is a type of non-probability sampling technique. Non-probability sampling focuses on sampling techniques where the units that are investigated are based on the judgement of the researcher.

Value Hierarchy

Kirkwood (1997) defined the value hierarchy (or tree) as a pictorial representation of a value structure (consisting of the fundamental objective, the values, and the measures).

Value Robustness Metric Criteria

In order to evaluate the goodness of design principles candidate metrics, a set of criteria must be established. A preliminary set of metric criteria proposed by Christian (2004) was considered for this study. Christian (2004) proposes that a good metric should:

- Relate to performance
- Be complete
- State any time dependency
- Be simple to state
- State any environmental conditions
- Be quantitative
- Be easy to measure
- Help the user identify a system that best meets their objective

For the research reported in this thesis, the most important consideration from this list is that the metric be simple to state and useful to the user. To be useful to a user could mean that the metric should be easy to implement and exist in a well understood systemic, logical framework. Criterion ‘relate to performance’ is taken to relate to the system (i.e., initial design of the system) ability to change (its architecture).

Accordingly, generated set of criteria for evaluating the validity of any associated value robustness constructs metrics (informed by Christian, 2004) are as follows:

Are time/generations accounted for?	Yes	No	
Is the extent of change measured?	Extent of change is not considered	Extent of change is measured implicitly	Extent of change is explicitly measured
Is the ease of change measured?	Ease of change is not considered	Ease of change is measured generally	Ease of change is measured for each end state
Is the metric relatively simple to implement?	The metric is prohibitively complex and would require extensive work to implement	The metric not trivial, but most engineers could apply it given enough time	The metric is simple enough that a layperson could apply it and understand the results with little to no explanation
How accessible is the metric?	The metric operates in a new and complex framework not available to other engineers	The metric operates in a framework that might not be commonplace but is understandable and available to other engineers	The metric operates in a framework completely accepted and widely used by other engineers.

Value Stream

Value Stream can be defined as the set of actions that bring a complex adaptive system from concept to realization (i.e., the processes of creating, producing, and delivering a complex adaptive system). In the context of this thesis, understanding value stream is important for two reasons. First, it enables designers/engineers and managers to group complex adaptive system by the processes that make them. Second, knowing the value stream allows designers/engineers and managers to focus on a set of linked processes and helps to prevent distraction in your analysis.

Appendix B Delphi Study – Supplemental Material

Sample email sent to systems architecting experts involved in the study

This email was sent to experts after they had been nominated by the programme manager and their participation approved and they had indicated interest in participating in the study.

Dear ______,
Thank you for agreeing to participate in this study of Complex Systems design and architectural challenges, which is my thesis research at Brunel University. Because of your expertise as a systems architect/designer, you have been specifically nominated by your programme manager. The nomination criteria included systems architecting and design experience in any systems architecture program, particularly for two years or more.

You are a part of a selected expert panel of approximately 25. Your thoughts and comments will provide an important foundation for further research concerning the skills and artifacts in enhancing anticipatory capacity of a typical complexity engineering organisation.

What your involvement entails.

I am estimating that your participation will take you no more than **five hours total** over a period of about six months. You will receive three study documents via email, as well as a final summary of the results of the study for your own information.

How the study will proceed.
You will receive an email and will be asked to follow the directions in the study, beginning with the Round One.

Round One contains:
1. A summary of information about the topic
2. An open-ended question

My estimate, based on relevant similar studies, is that it will take you no more than 1-1.5 hours to complete Round One. The study is designed to enable you to save your answers and return to the questions later. This will allow you to set aside time as needed to think about your answers and attend to your work without having to address the questions all at one time.

You will have 10 days to complete and return your Round One responses and comments.
Approximately two weeks after all Round One comments are received and analysed, you will receive another email relating to Round Two.

Round Two/Three will contain:
1. Your comments from Round One
2. A summary of the responses of other participants presented in a manner that does not identify or link any comment to any individual participant

3. A brief set of approximately 23 questions developed from the comments of study participants that you will be asked to rate in importance using a Likert-scaled set of questions.

You will be asked to return your comments and ratings in 10 days. The estimated completion time for this round is 1-1.5 hours.

About two weeks after the group's Round Two ratings are received and analysed, you will be emailed the set of Round Three questions, which will be similar to Round Two questions.

Round Four will contain:
1. A summary of Round Two/three results
2. The aim of the final round was to further investigate a few chosen challenges and issues suggesting mitigation strategies.

The estimated completion time for this round is 45 minutes to 1.5 hours.

Your commitment and willingness to lend your expertise to the goals of this study is significant. The insights and skills you share have the potential to impact further research regarding systems architecture design.

Thank you again for participating. If you have questions, please feel welcome to email me at austin.amaechi@lsw.com

Warm regards,

Austin Amaechi

Round One

Round One Question and resultant data: *What challenges and issues are considered important by project managers, system architects and designers of complex systems as having significant impact on systems architecture design?*

1. Lack of clear mechanism for incorporation of ability to change lifecycle system properties rapidly and easily (19)
2. Analysis of the requirements uncertainty stemming from the Directive and its relationship to system architecting (10)
3. Analysis of the requirements uncertainty stemming from consultation papers and relationship to system architecting (14)
4. Effective coordination strategies for managerial complexity issues (16)
5. Lack of clear mechanism for incorporation of ability of the risk models to be insensitive to input of wrong data or unexpected large data (20)

6. Assessment of potential system architecture functionality (11)
7. Lack of well-defined architectural process and development plans for systems in an uncertain environment (17)
8. Lack of effective decision-making powers and independence of the architectural team (4)
9. Lack of clarity/understanding of solution space (2)
10. Dialogue and interactions with supervisors (4)
11. Problems in the cooperation between technical and business people (6)
12. Adherence to Capability Maturity Model Integration for Development (CMMI-DEV) currently used in the company (7)
13. Team education and effective allocation of team to specific assignments are limited and poorly handled (15)
14. Adherence to quality framework given by ISO 9126 currently used in the company (2)
15. Documentation and Communication of design processes (9)
16. Lack of flexible method evaluating architecture suitability (5)
17. Lack of appropriate mechanism for applying of value models when choosing envisioned architecture (2)
18. Lack of effective communication and feedback (between stakeholders) (8)
19. Lack of clear long-term strategy for Regulatory Governance
20. Lack of a clear strategy for managing complexity through the lifecycle of the system (12)
21. Information asymmetries and structured management of knowledge (5)
22. Building trust in a multidisciplinary/interdisciplinary team (3)
23. Lack of sufficient resources (2)

Round One data collection - - (Numbers in the bracket indicate how often themes were noted by experts). Challenges and issues have been selected for further study based on criteria that they were selected by at least two of the participants.

Questions Developed for Rounds Two and Three

On a likert-scaled set of (1.00 – 1.49 = very important, 1.50 – 1.99 = quite important, 2.00 – 2.49 = somewhat important, and 2.50 – 3.00 = neither important nor unimportant), please rate the importance of the following selected Systems Architecting Challenges and Issues in complex systems architecture design and management:

	Selected Systems Architecting Challenges and Issues	**Scale**
1	Lack of clear mechanism for incorporation of ability to change lifecycle system properties rapidly and easily	
2	Analysis of the requirements uncertainty stemming from the Directive and its relationship to system architecting	
3	Analysis of the requirements uncertainty stemming from consultation papers and relationship to system architecting	
4	Effective coordination strategies for managerial complexity issues	
5	Lack of clear mechanism for incorporation of ability of the risk models to be insensitive to input of wrong data or unexpected large data	
6	Assessment of potential system architecture functionality	
7	Lack of well-defined architectural process and development plans for systems in an uncertain environment	
8	Lack of effective decision-making powers and independence of the architectural team	
9	Lack of clarity/understanding of solution space	
10	Dialogue and interactions with supervisors	
11	Problems in the cooperation between technical and business people	
12	Adherence to Capability Maturity Model Integration for Development (CMMI-DEV) currently used in the company	
13	Team education and effective allocation of team to specific assignments are limited and poorly handled	
14	Adherence to quality framework given by ISO 9126 currently used in the company	
15	Documentation and Communication of design processes	
16	Lack of flexible method evaluating architecture suitability	
17	Lack of appropriate mechanism for applying of value models when	

	choosing envisioned architecture	
18	Lack of effective communication and feedback (between stakeholders)	
19	Lack of clear long-term strategy for Regulatory Governance	
20	Lack of a clear strategy for managing complexity through the lifecycle of the system	
21	Information asymmetries and structured management of knowledge	
22	Building trust in a multidisciplinary/interdisciplinary team	
23	Lack of sufficient resources	

Please identify any issues you feel were not adequately addressed by these questions:

Questions Developed for Rounds Four

In the final phase of the study, experts were provided with an overview of selected architectural challenges and issues and were asked to respond to the following the question:

What techniques and strategies do you think are most effective to facilitate solution to the challenges identified?

1. Effective coordination strategies for managerial complexity issues
2. Lack of well-defined architectural process and development plans for systems in an uncertain environment

Appendix C SRITS Case Study – Supplemental Material

This section will give a short overview of the main activities in undertaking the SRITS case study.

Documentary Analysis Framework

DOCUMENTARY ANALYSIS THEMATIC CONTENT	
Document	
Year	
Unit	
Type of doc/authorship	
Descriptive Goals	
Stakeholders	
Stakeholder needs	
Program goals and priorities	
List of Architecture-level System Properties	
List of Design-level attributes	
List of Operational-level attributes	

Case study protocol

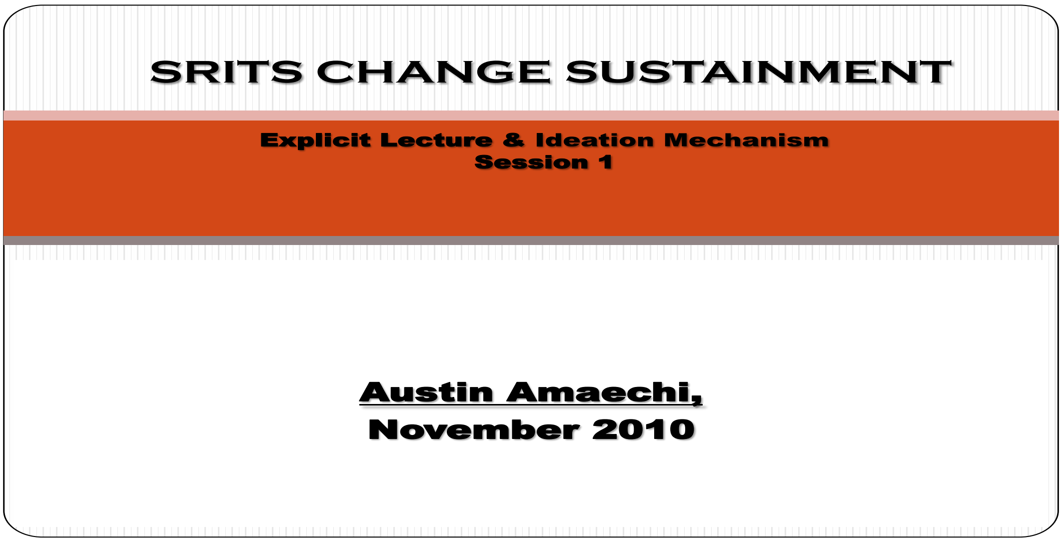
The overall objective of the case study is to investigate the amount of help that the CXLUD framework can offer in a real industrial setting. The results obtained in this case study cannot necessarily be generalized and cannot guarantee that similar success would be achieved in other applications.

Real-life case study approach is said to be suitable for an industrial evaluation of engineering techniques and tools if they are organised and conducted in a sound way. To help structure the conduct and success of the process, we deliberately choose to use the following steps:

1. Case study design: selection of the project; objectives are defined (Section 6.2).
2. Definition of hypothesis and selection of suitable criteria for the validation.
3. Preparation for data collection: procedures and protocols for data collection are defined (Section 6.3).
4. Collecting evidence: execution with data collection on the studied case (Section 6.3).
5. Analysis of collected data and generation of report (Section 6.3).

The next section reports on the conducting the SRITS case study and results

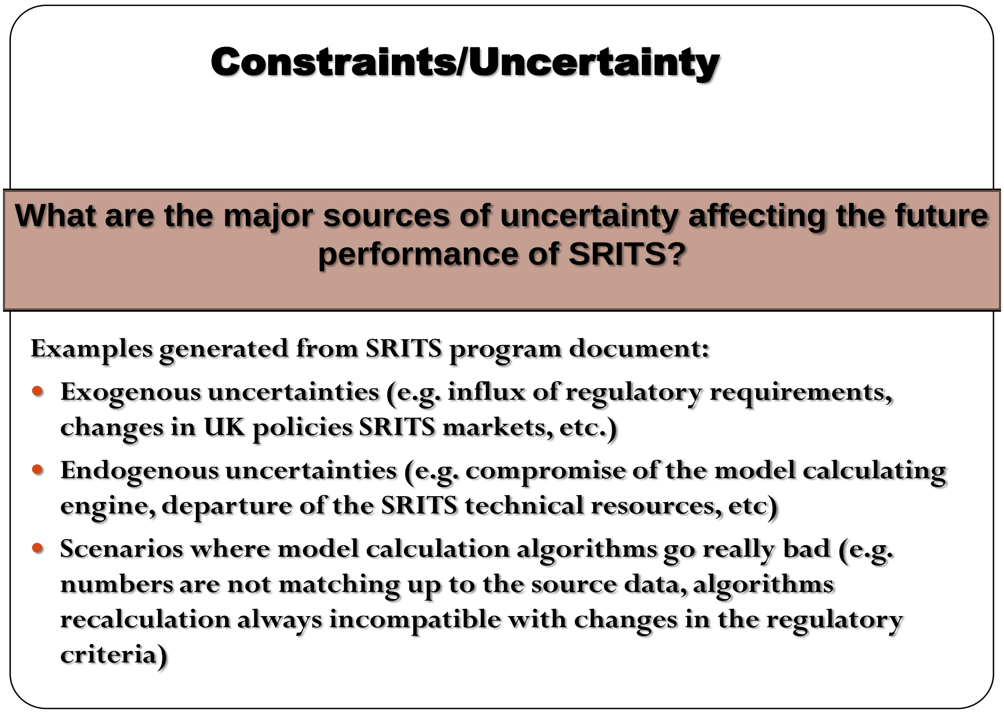
A: Change Sustainment Slides – Prompts for Creative Anticipation Mechanism



SRITS CHANGE SUSTAINMENT

Explicit Lecture & Ideation Mechanism
Session 1

Austin Amaechi,
November 2010

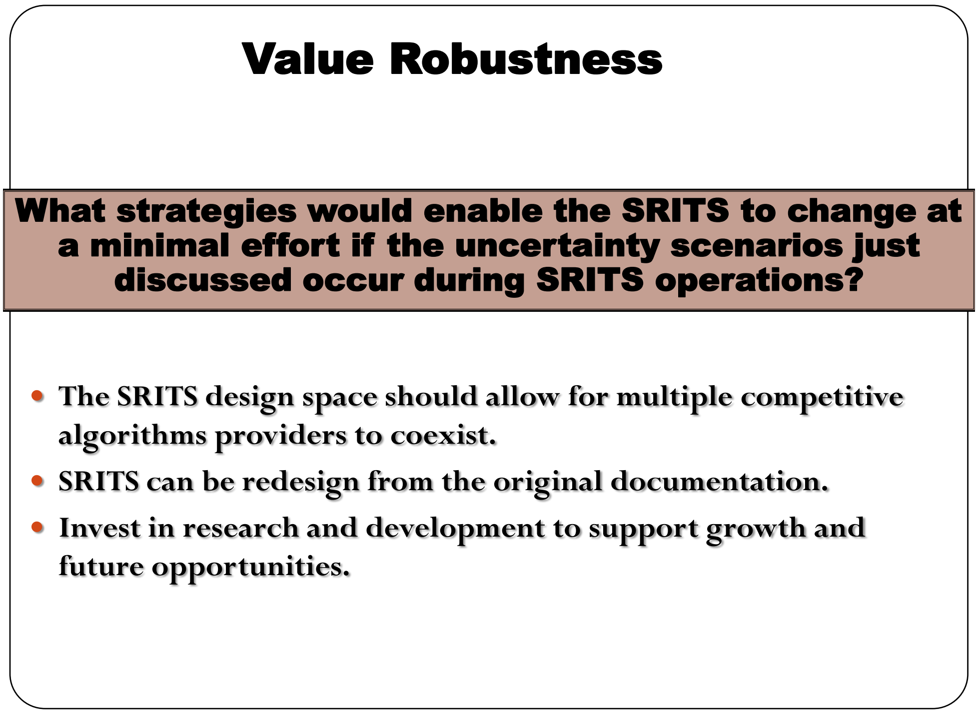


Constraints/Uncertainty

What are the major sources of uncertainty affecting the future performance of SRITS?

Examples generated from SRITS program document:

- Exogenous uncertainties (e.g. influx of regulatory requirements, changes in UK policies SRITS markets, etc.)
- Endogenous uncertainties (e.g. compromise of the model calculating engine, departure of the SRITS technical resources, etc)
- Scenarios where model calculation algorithms go really bad (e.g. numbers are not matching up to the source data, algorithms recalculation always incompatible with changes in the regulatory criteria)



Value Robustness

What strategies would enable the SRITS to change at a minimal effort if the uncertainty scenarios just discussed occur during SRITS operations?

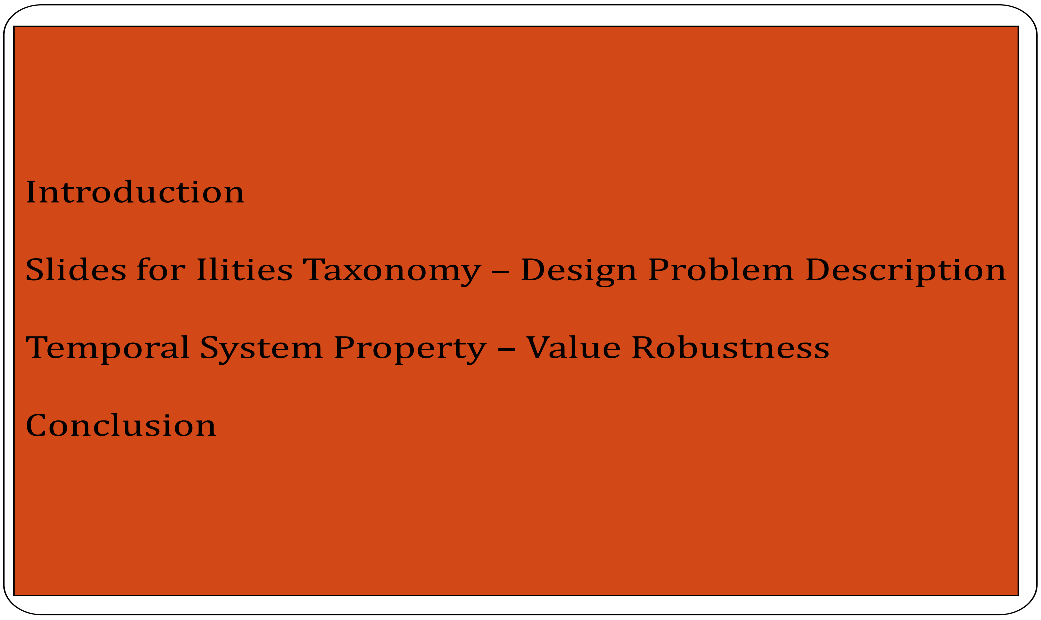
- The SRITS design space should allow for multiple competitive algorithms providers to coexist.
- SRITS can be redesign from the original documentation.
- Invest in research and development to support growth and future opportunities.

B: Ilities Taxonomy Slides – Creative Anticipation Design Problem Description

SRITS PROGRAM

Explicit Lecture & Prompt Question
LAB - 1

Austin Amaechi,
November 2010



Introduction

Slides for Ilities Taxonomy – Design Problem Description

Temporal System Property – Value Robustness

Conclusion

INTRODUCTION (2)

- Maintaining SRITS system performance in the presence of uncertainties in design and operating environments is both challenging and increasingly essential as system lifetimes grow longer.
- In response to perturbations brought on by these uncertainties, such as context shifts and shifting stakeholder needs, systems may be able to continue to deliver value by being either robust or changeable.

In this session, we are trying to find insights into how SRITS might be designed so that they can change in order to continue delivering value in spite of perturbations.

Steps in Modeling the Structure of a Design Decision - Creative Anticipation

Step 1: Identify the Decision Situation

Step 2: Explicit Lecture/Prompting - Determine the Objectives

Step 3: Use Case/Data Collection - Choose the Attributes

Step 4: Evolving but partial design - Identify Design Alternatives & Design Variables

The Situation

☐ management wants design offering best expected ‘value robustness’ properties for the definition of SRITS system architectures

☐The team is asked to investigate design options

☐ Also identify systems architecting design principles sets of interest to guide the development of a value robust SRITS architecture

Definitions of Uncertainty

- 1. “Anything that can impact promises or business objectives in the future! – Verbraeck, 2010

UNCERTAINTIES	RISKS/OPPORTUNITIES	MITIGATIONS/ EXPLOITATIONS	OUTCOMES
. Lack of Knowledge . Lack of Definition . Known Unknowns . Unknown Unknowns . Statistically Characterized Variables	. Failure . Degradation . Emergent Capabilities . Disaster . Extra Capacity . etc	. Design Choices . Redundancy . Modularity . Tradespace Exploration . Generality . etc	. Flexibility . Robustness . Evolvability . Interoperability . Reliability . Versatility

<Uncertainty> causes <Risk> handled by <Mitigation> resulting in <Outcome>

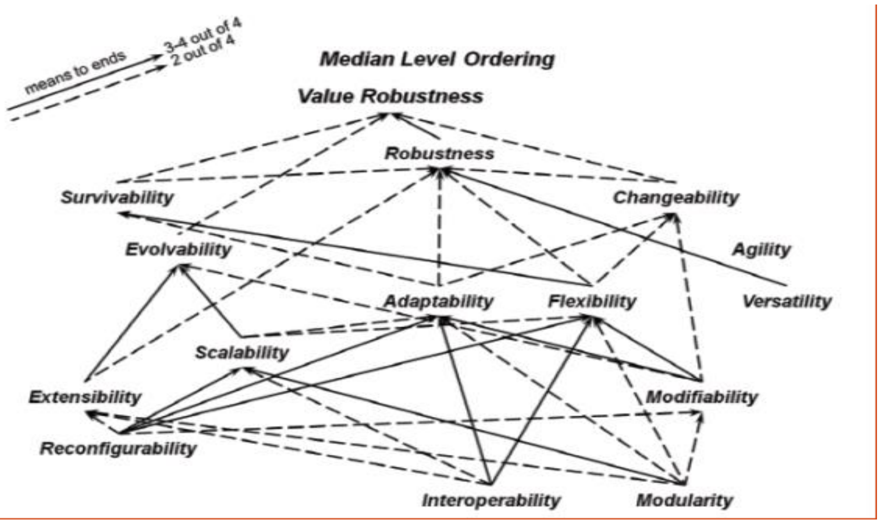
What is ILITITES

- Ilities (i.e., system properties) specify the degree to which systems are able to maintain or even improve function in the presence of change - McManus et al 2008

- Ilities offer decision makers means of discriminating between different design concepts and systems for fulfilling the needs that are required

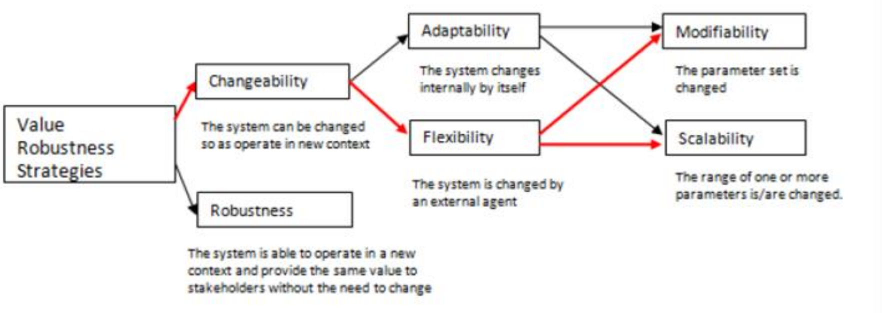
- An important group of ilities that directly relate to the understanding of a system's dynamics or how the system acts due to change over time are ilities that relate to change. These provide insight into understanding a system's change over time and can give an important understanding of value of a system through changing contexts or environments

Ilities hierarchy - *justification of why*



Value Robustness Strategies

there are two possible value robustness strategies, passive value robustness and active value robustness corresponding to robustness and changeability of the systems – Ross and Rhodes (2008)



Analysis and Suggested Design

- **Potential solutions and avenues for further analysis**

SRITS FUTURE VALUES TO ILITY MAPPING

Stakeholder’s future values	**Ilities**	**Comments**
SRITS Continuous Growth		
Good Communication Channels		
Compromise of the model calculating engine		
Departure of the SRITS technical resources		

Appendix D Substantiation Study – Supplemental Material

This appendix reviews the methodology of the substantiation study that was conducted for CXCLUD validation of the research study reported in Chapter 7. It also addresses issues related to the interpretation of the findings. Also included are the substantiation questions.

The Substantiation Approach

Much thought and discussion was needed to identify an efficient and practical approach of gathering feedback from people in the complex systems design and management industry, who have little time in their schedules to invest in such studies. There is little point in assessing frameworks or collecting metrics unless they address directly the organisational (people) issues. Project success or failures are due to the people or organisation involved. A better approach is therefore to assess the products, or the processes, or the people.

Procedure for Gathering Feedback

The initial idea for gathering complex systems design and management industry feedback was to prepare a comprehensive survey of the CXLUD Framework and to mail it to people in the complex systems design and management community. However, since these potential participants were not yet informed about the framework, this survey had to be supplemented with reading material explaining the CXLUD Framework. Compiling an explanation of the framework to accompany the survey resulted in a potential 20 plus page document. The reality is that people in complex systems architecting practice, especially industry leaders and experts, would not have the time to read a 20 plus page document and fill out and return a survey.

Yet another idea was to visit and present the framework face-to-face to selected complex systems design organisations. Although visiting people in person ensured having their attention for at least the duration of the visit, it would have required that those who agreed to participate to dedicate 90 minutes of their time for a visit and visiting at least 60 practicing system architects, engineers and managers to form an acceptable research participants. The next challenge would be to develop an approach for presenting the framework and gathering feedback within the allocated time.

In the end, a more suitable method which was adopted for this study was a questionnaire. However, prior to distributing the questionnaires, participants were briefed with an introductory presentation with a review of the scope of the study and with general guidelines to follow through. The presentation was done via webinar - web-based seminar method. Participants were asked to complete the evaluation survey that formed the basis for analysis. It is important to note that the study was not meant to assess the group as the unit of analysis; rather, the focus was on individual participants as units of analysis.

Questions and Participant's Guidelines

The CXLUD conceptual framework consists of different stages. Therefore, for more accurate results, feedback from selected questions about each of the components was gathered. Since the surveys were intended for program managers and systems architects, whose time and availability was limited, there were 20 quantitative questions based on a 5-point Likert summated scale, from 1 "strongly disagree" to 5 "strongly agree,". There were also 4 qualitative open-ended questions that complemented the quantitative questions to provide broader and deeper coverage of the topic. These qualitative questions, coupled with the informal discussions, helped to elicit better feedback from the participants about the framework.

The assessment instrument containing questions, belonging to eight different categories, was developed to test the (1) effectiveness, (2) completeness, (3) necessity, (4) understandability and (5) practical or industrial applicability. The assessment criteria factors were measured and ordered on a five-point scale from 1 = "strongly agree" to 5 = "strongly disagree" (Table 1). The scale items 1 and 2 represent the satisfactory indicator; the scale item 3 represents impartial or silent indicator; finally, the scale items 4 and 5 represent the unsatisfactory indicator or feedback. The overall assessment in a particular category would be considered satisfactory if a total of 50% or more of all the experts reported or indicated the satisfactory feedback; the overall results would be considered unsatisfactory if a total score is less than 50%.

Table 1: Assessment instrument

Order	**Assessment Scale**	
	Rating Column	**Results**
1	Strongly Agree	Satisfactory
2	Slightly Agree	
3	Neutral	Impartial
4	Slightly Disagree	Unsatisfactory
5	Strongly Disagree	

Assessment Questionnaire: “Substantiation of the CXLUD Framework”

Date	**Reference No**	

SECTION 1: ASSESSOR’S INFORMATION

Name (optional):		
Organisation		
Job Title (official position)		**Years in position:**
Please rate your familiarity with System Architecting	**1 2 3 4 5 6 7** NF SWF Expert	
Please rate your familiarity with Complex Systems characteristics	**1 2 3 4 5 6 7** Never occasionally constantly	
Please rate your highest level of involvement in systematic general process adoption efforts	**1 2 3 4 5 6 7** None Participant Leader	
How frequently do you participate in Complexity Science practices	**1 2 3 4 5 6 7** Never occasionally constantly	
Highest education Qualification		
General Comment		

Would you add, remove or redefine any of the CXLUD stages or steps within the stages? If so please explain why.

SECTION 2: THE OVERALL PROCESS FRAMEWORK

	strongly disagree	**slightly disagree**	**neither disagree nor agree**	**slightly agree**	**strongly agree**
UNDERSTANDABILITY - For the topics listed below designate the degree to which you agree that they are understandable					
Overall objective of this framework					
Design Innovation Control					
System Lifecycle Control					
Architecture Realization Control					

PRACTICALITY - One of our objectives is to make sure that the process framework is practical and can be used in industry. In light of this to what extent would you agree that process framework would be practical and feasible to employ?					
NECESSITY - The process framework is beneficial to the system engineering industry?					
COMPLETENESS					
All the necessary components are present in this process framework in order to achieve its overall goal of aiding an organization in the complex system development for its various projects?					
The steps and activities in the framework are organized in a logical and valid sequence in order to achieve its overall goal of an assisting continuous innovation					
EFFECTIVENESS					
Design Innovation Control					
System Lifecycle Control					
Architecture Realization Control					

Appendix E Phenomenology Study – Supplemental Material

This appendix reviews the methodology of the phenomenological study. The purpose of this research was to explore the lived experiences of complex adaptive system development project managers reported in Chapter 8. It also addresses issues related to the interpretation of the findings and the exploratory questions. Phenomenological approach is appropriate when there is little information available on a particular topic.

Research Methodology Applied to Data Analysis

The study data was analyzed using a modified version of the Van Kaam (1972) method, as described by Moustakas (1994). This method consists of the following steps that helped the researcher understand the participants' perceptions of decision associated with managerial complexity.

1. Steps for each individual transcript:
a. Review each statement and record expressions pertinent to the study's phenomenon. Do an initial grouping of these expressions. This step is called "Horizontalization" (Moustakas, 1994, p. 121).

b. Review each expression identified in the previous step, and test it against the following two questions: (a) "Does it contain a moment of the experience that is a necessary and sufficient constituent for understanding it?" (b) "Is it possible to abstract and label it?" (p. 121). The resulting sets of expressions are considered the core set of expressions for the experience. These are called "Invariant Constituents" (Moustakas, 1994, p. 121).

c. The invariant constituents are then clustered into themes.

d. The themes and associated invariant constituents are validated against the complete transcription to ensure that they are correct, otherwise they are removed.

e. The resulting themes of the experience are described using quotes from the participant. This step is called an "Individual Textural Description" (Moustakas, 1994, p.121).

f. Based on the individual textural description, a description of the participant's experience is created that attempts to depict the underlying reasons for the experience and identifies the thoughts and feelings associated with the experience. This is called an "Individual Structural Description" (Moustakas, 1994, p. 121).

Interview Guide: "Lived Experiences in Managerial Complexity"

The primary objective is to elicit samples of thought that demonstrate the extent to which the interviewee thinks complex systemically.

Interviewee Reference/Name:

Interview Data Collection Form (1 of 2)

Demographic Questions

2. What is your gender?

----

3. What is your current location?

----

4. How many years have you served as project management related positior

----

5. How many months/years have you served in a complex adaptive systems project management related position?

----

6. What formal training have you had in complex systems principles?

Interview Data Collection Form (2 of 2)

Central Research Question

How do complex system development project managers or leaders perceive and describe the lived experience of decision making uncertainty when determining the appropriate response to managerial complexity?

Lead Interview Question:
Please describe your first-hand experiences with decision-making with regard to managerial complexity issues in your development and management project

----

8B: Selected Individual Textual Descriptions

Individual textual descriptions capture the participants' unique perceptions, insights, and accountings of the decision-making experienced when determining the appropriate response to managerial complexity issues. The participants' transcribed written interviews (questionnaire) forms were reviewed to develop the individual textual descriptions.

*Textual Description Summary for Participant #***WTN1**, who summarized,

"I made the decision to focus greater attention on the development process rather than on the system that team will eventually produce. This was one step in my attempt to move from requirements-centric instruction to value-centric development instruction."

"I would say the global nature of the system development project (for instance the data architectural and modeling teams are based in UK, interface/dashboard team in India, etc) afforded me the opportunity to remove myself from the main stage and into a position where I can observe the entire system."

"With agreed rules in place, increasingly I have learned to drop principles of line of sight management instead trusting my team to do their work and focus more on the overall results."

Textual Description Summary for Participant # **WTN 2**, who summarized,

"The inconsistencies in the regulatory directives and the internal directorate interpretation of such directives affect the success of the project. It means that timing is everything. Therefore designing into the development processes the ability to close temporarily and reopen when more information can increase a project's value and can mitigate the problems that are associated with poor timing."

*Textual Description Summary for Participant #***WTN3**, who summarized,

"…it takes a lot of listening and a lot of interacting before you can move to that

next level where you have a relationship with the team that is two-way ...where you can anticipate where a particular team member is going with a thought or idea."

"I made conscious effort to adopt a coordinate-and-cultivate *style of team leadership which seems to have brought better coherence to the team than classical command-and-control style of leadership. We set internal team rules as a unit (though I still have my influence) and every one of us is following and keeping to all necessary changes."*

*Textual Description Summary for Participant #***WTN 4**, who summarized that:

"My overall altitude to system development process has changed and I can probably say that for most of my project team member. You kind of adopt wait and see to the uncertain situations."

*Textual Description Summary for Participant #*WTN5, who summarized that:

"...achieving better project leadership through continuous creation of knowledge, skills and experiences gained through continuous professional development and operational experience."

"I think focusing greater attention on the views of those internal to the company rather than solely valuing the views of senior consultants who come from outside to consult, evaluate what goes on there and engage in theorizing about it. This shift led to such innovations as qualitative research - with its valuing of the subjective and affective, of the participants' insider views and of the uniqueness of each context."

*Textual Description Summary for Participant #***WTN 6**, who summarized that:

"...as I thought that it is very important all team members maintain contact with one another and be mutually supporting, I insisted by leading from the front."

*Textual Description Summary for Participant #***WTN 7**, who summarized,

"It's difficult to make response decisions without a value of data, without certainty of thresholds, without clarity of roles and missions, and it's difficult for a decision maker to make a prudent choice when they don't really understand what's possible, technically."

"Knowing where the weaknesses are in the team is very important. That would always form the point of crisis, hence being present at the point of an anticipated crisis is crucial."

*Textual Description Summary for Participant #***WTN 8**, who summarized,

"Most of the strategic and tactical problems are such that they cannot be solved at a single scale. Most require serious coordination, multiple perspectives and organised responses. All my project team members have access to the company global knowledge management systems and we have regular brainstorming and ideation sessions."

*Textual Description Summary for Participant #*WTN9

"Team members from designers to developers work side-by-side and have input during each stage of the analysis and construction processes. Most often plans are developed at the lowest levels and are then passed on to each next higher level."

"Focusing greater attention on diversity among project team and viewing these differences not as impediments to a successful project but as resources to be recognized catered to and appreciated."

"People can and will process information, as well as react to changes in information….the team are becoming more responsive to the project rules which we have all agreed to. What we did was basically to digest the overall organisational project guidelines in a simple format. This became the team decisions guide ensuring good coordination."

Tables E-1, E-2 and E-3 = discussing data collected and interpreted under the proposed 3 categories in the competency model

Table E-1 Understanding Competencies

The first thematic or competency category that emerged from the data was labelled, **Understanding**. The category pertained to the key components of complexity thinking that enabled the project managers to understand the project environment. Table below contains all the core themes (competencies) that emerged under this category.

Observable interactions emerged as the most cited understanding competency that aided the project leaders/managers for exploring the project environment (8 out of 9 participants, 89%).

Thematic category: Understanding

Competency	**Number of participants to offer this experience**	**Frequency of Use**
Observable interactions	8	89%
Emergent behaviour	7	78%
Diversity	5	56%
Focus on Value	4	44%
Distributed decision-making	3	33%
Purposefulness	3	33%
Team autonomy	2	22%

Most of the project managers described how systems environments are constantly changing through the course of the project, which are sometimes orderly and, at other times, disorderly. According to project managers, they in different ways have to interact with multiple actors and were constantly dealing with emergent behaviours such as lack of clarity and consistency in stakeholders needs causing unintended consequences. Participants **WTN**1, **WTN**3, **WTN**5, **WTN**8 and **WTN**9 are the examples where participants expressed how meaningful “understanding” was in their experiences in a supported managerial complexity program.

Participant WTN1 recounted a point that influenced his motivation:

> *“I made the decision to focus greater attention on the development process rather than on the system that team will eventually produce. This was one step in my attempt to move from requirements-centric instruction to value-centric development instruction.”*

Participant WTN3 stated:

> *“…it takes a lot of listening and a lot of interacting before you can move to that next level where you have a relationship with the team that is two-way …where you can anticipate where a particular team member is going*

> *with a thought or idea."*

Participant WTN5 also conveyed that decision-making uncertainty challenges are influenced by the potential of a successful product resulting from a purposefulness and interrelatedness within the development team. He wrote:

> *"I think focusing greater attention on the views of those internal to the company rather than solely valuing the views of senior consultants who come from outside to consult, evaluate what goes on there and engage in theorizing about it. This shift led to such innovations as qualitative research - with its valuing of the subjective and affective, of the participants' insider views and of the uniqueness of each context."*

Participant WTN8 provided an explanation for what inspired him to seek for a better way of managing the project complexity:

> *"Most of the strategic and tactical problems are such that they cannot be solved at a single scale. Most require serious coordination, multiple perspectives and organised responses. All my project team members have access to the company global knowledge management systems and we have regular brainstorming and ideation sessions."*

Participant WTN9 stated:

> *"Focusing greater attention on diversity among project team and viewing these differences not as impediments to a successful project but as resources to be recognized catered to and appreciated."*

The views of the participant WTN5 shows how important it is to understanding and shaping emergent properties. It is essential to the survival of project development team as a social system.

Table E - 2: Perception Competencies

The second thematic or competency category that emerged from the data was labeled, **Perception**. The category pertained to the key components of systems complexity thinking which enable the project managers to adapt to the demands of complex systems development process environment. Table below contains selected core themes (competencies) that emerged from this thematic category. Characteristics of complex socio-technical systems identified from the data shows Adaptive leadership emerging as the most cited perception component that aided the project leaders/managers to coping with managerial complexity (8 out of 9 participants, 89%).

Thematic category: Perception and attitude to realities

Competency	Number of participants to offer this experience	Frequency of Use
adaptive leadership	8	89%
bottom up feedback	7	78%
holistic thinking	5	56%
diversity	5	56%
Co-evolution	2	22%

Participant WTN5's approach is to recognise the importance of the need for readiness to adapt the leadership style, responsibilities and bottom-up feedback. **Participant WTN5** states:

> *"...achieving better project leadership through continuous creation of knowledge, skills and experiences gained through continuous professional development and operational experience."*

> ***Participant WTN 1*** *wrote "I would say the global nature of the system development project (for instance the data architectural and modeling teams are based in UK, interface/dashboard team in India, etc) afforded me the opportunity to remove myself from the main stage and into a position where I can observe the entire system."*

Participant **WTN 8** argues profound show of lack of proportionality in some of the system requirements and the stated business effects. Participant **WTN 9 wrote:**

> *"Team members from designers to developers work side-by-side and have input during each stage of the analysis and construction processes. Most often plans are developed at the lowest levels and are then passed on to each next higher level."*

Participant WTN 4 wrote:

> *"My overall altitude to system development process has changed and I can probably say that for most of my project team member. You kind of adopt wait and see to the uncertain situations."*

Participant WTN 4's statement is classical case of "a system and the environment influencing each other's development.

Table E – 3 Action Taken Competencies

The final thematic or competency category that emerged from the data was labeled, **Action taken.** The category pertained to the key components of complexity thinking which describe the approach the project managers took to solving complex problems. Table below contains all the core themes (competencies) that emerged from the thematic category. Simple rules emerged as the most cited approach undertaken by the project leaders/managers to attacking the challenges of the managerial complexity (9 out of 9 participants, 100%).

Competency	**Number of participants to offer this experience**	**Frequency of Use**
Simple rules	9	100%
Holistic view	9	100%
Interaction in an iterative way	5	56%
Learning	5	56%
Flexibility	3	33%
Modularity	3	33%

Sample extract from the study participant's response will now be discussed.

Participant WTN 1 for instance stated that

> *"With agreed rules in place, increasingly I have learned to drop principles of line of sight management instead trusting my team to do their work and focus more on the overall results."*

The role of the complexity science principles for managerial complexity issues as perceived is also apparent in the **Participant WTN 2**responses:

> *"The inconsistencies in the regulatory directives and the internal directorate interpretation of such directives affect the success of the project. It means that timing is everything. Therefore designing into the development processes the ability to close temporarily and reopen when more information can increase a project's value and can mitigate the problems that are associated with poor timing."*

Participant WTN 9 wrote:

> *"People can and will process information, as well as react to changes in information….the team are becoming more responsive to the project rules which we have all agreed to. What we did was basically to digest the overall organisational project guidelines in a simple format. This became the team decisions guide ensuring good coordination."*

According to Participant WTN 3 coordination has brought better results than controlling as a leadership paradigm. WTN3 wrote:

> *"I made conscious effort to adopt a coordinate-and-cultivate style of team leadership which seems to have brought better coherence to the team than classical command-and-control style of leadership. We set internal team rules as a unit (though I still have my influence) and every one of us is following and keeping to all necessary changes."*