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Sensemaking in a value based context for large scale complex engineered systems

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Sensemaking in a value based context for large scale complex engineered systems

by

Nazareen Sikkandar Basha

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Aerospace Engineering

Program of Study Committee:
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Iowa State University

Ames, Iowa

2017

DEDICATION

To

Abbujaan, I will always love you and miss you

&

Ammijaan, my forever inspiration.

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NOMENCLATURE

DA	Decision Analysis
DM	Decision Maker
DOD	Department of Defense
INCOSE	The International Council on Systems Engineering
LSCES	Large-Scale Complex Engineered System
MDO	Multidisciplinary Design Optimization
SE	Systems Engineering
SM	Sensemaking
VDD	Value Driven Design

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ABSTRACT

The design and the development of Large-Scale Complex Engineered Systems (LSCES) requires the involvement of multiple teams and numerous levels of the organization and interactions with large numbers of people and interdisciplinary departments. Traditionally, requirements-driven Systems Engineering (SE) is used in the design and development of these LSCES. The requirements are used to capture the preferences of the stakeholder for the LSCES. Due to the complexity of the system, multiple levels of interactions are required to elicit the requirements of the system within the organization. Since LSCES involves people and interactions between the teams and interdisciplinary departments, it should be socio-technical in nature. The elicitation of the requirements of most large-scale system projects are subjected to creep in time and cost due to the uncertainty and ambiguity of requirements during the design and development. In an organization structure, the cost and time overrun can occur at any level and iterate back and forth thus increasing the cost and time. To avoid such creep past researches have shown that rigorous approaches such as value based designing can be used to control it. But before the rigorous approaches can be used, the decision maker should have a proper understanding of requirements creep and the state of the system when the creep occurs. Sensemaking is used to understand the state of system when the creep occurs and provide a guidance to decision maker. This research proposes the use of the Cynefin framework, sensemaking framework which can be used in the design and development of LSCES. It can aide in understanding the system and decision making to minimize the value gap due to requirements creep by eliminating ambiguity which occurs during design and development. A sample hierarchical organization is used to demonstrate the state of the system at the occurrence of requirements creep in terms of cost and time using the Cynefin framework. These trials are continued for different requirements and at different sub-system level.

The results obtained show that the Cynefin framework can be used to improve the value of the system and can be used for predictive analysis. The decision makers can use these findings and use rigorous approaches and improve the design of Large Scale Complex Engineered Systems.

CHAPTER 1

INTRODUCTION

A Large-Scale Complex Engineered System (LSCES) is highly complex due to its enormous size including many entities, sub-systems, people and interdisciplinary departments. This complexity within the various elements of LSCES leads to various forms of risks, uncertainties and ambiguities within the different stages of the design and development of a LSCES. Past research has shown that, as the complexity of the system increases along with its size, the costs and time taken to develop LSCES increases proportionately [1]–[3]. To avoid the increase of cost and to make LSCES function successfully, it should have an elegant design and should satisfy the four attributes such as effectiveness, robustness, efficiency and should minimize the number of unintended consequences [4], [5]. This sequentially would avoid the increase in time due to developmental errors, design failures and other eventual failures of the LSCES.

Traditionally, the design and development of a LSCES as depicted by DOD involves a series of "V" model of the Systems Engineering (SE) for every stage of the development process as shown in the Figure 1 [6]. The Vee model is extremely high level and the preferences of the stakeholders are captured in form of requirements for every stage.

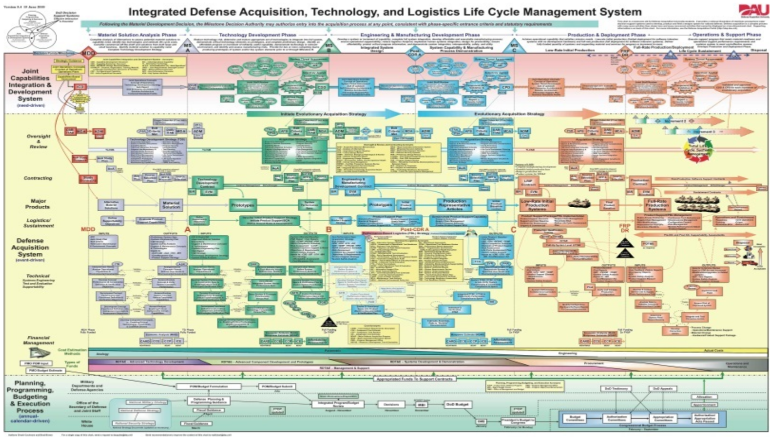

Figure 1. Integrated Defense Acquisition, Technology, and Life Cycle Management System (DOD) [7]

Requirement based systems engineering is not rigorous and is one of the many reasons for time overrun thereby increasing the cost of the system. This led the researchers to move towards rigorous approaches of Systems Engineering(SE) which includes Value-based Systems Engineering, Value Driven Design (VDD), Decision Analysis (DA) and Multidisciplinary Design Optimization (MDO). Because of the scale, scope and temporal dependencies and implications in a LSCES, the foundations are not clear to make decisions. A solid foundation of requirements engineering is needed before the rigorous methods can be applied to design and development of LSCES[1], [8], [9]. These are due to the presence of every changing requirements of the stakeholders, ambiguity with respect to the requirement and state of the system at different phases of design and development [1], [10].

A LSCES should be sociotechnical in nature by being self-aware of the process, the stakeholders and the organization involved in it [2]. Often, the LSCES must make sense of the situation to understand the uncertainty and ambiguity involved and distinguish according to the nature of situation [1], [11]. The implementation of Sensemaking (SM) frameworks can aide the decision makers to make sense of the situation and take appropriate decisions before exertion of rigorous approaches. In this thesis, Cynefin framework, a sensemaking framework is used to demonstrate it as a step before the decision analysis and other rigorous approaches for the design and development of LSCES as shown in the Figure 2. It can be incorporated to aid the decision makers, team of managers or higher level organization managers to understand the decision making for a LSCES.

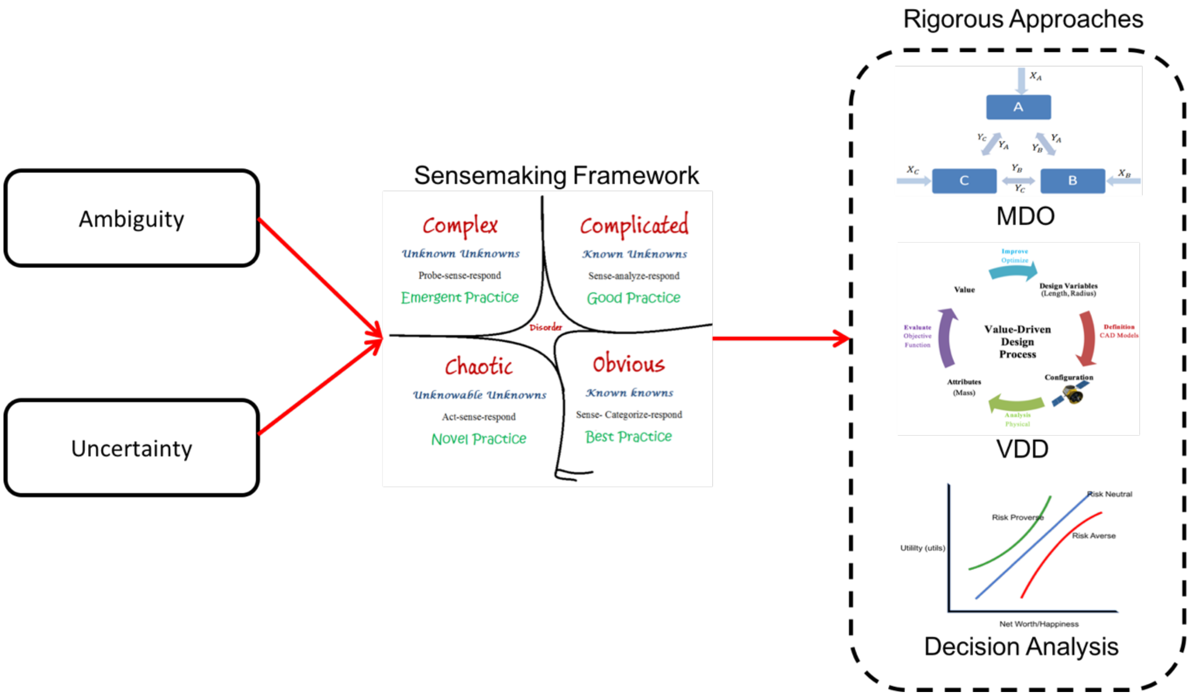

Figure 2. Ambiguity & Uncertainty before Sensemaking and rigorous approaches

The Cynefin framework was formulated by David Snowden is a sensemaking framework, which is a type of end-user decision making tool [12]. The Cynefin framework has five domains - Obvious, complicated, complex, chaotic, and disorder [13]. The state of the system, the design and development of LSCES involving the different phases of design are mapped on to the five domains of the Cynefin framework.

To illustrate this in a LSCES, the requirements of the stakeholders within a given organization structure is considered. Organizations which develop the LSCES provide facilities for the design and development involving multiple levels of interdisciplinary designs and numerous stakeholders [14]. These organizations are constructed in specific way depending on the nature of the company to accomplish different goals, such as the interactions between different departments for a product, cost reduction and innovation [15]. Depending on the essence of the system, the communication between the organizations can be direct or indirect. Direct communication refers to the communication between the two consecutive levels of the organization and indirect communication refers to the communication between interdisciplinary departments and different levels[16] .

Requirements of a large-scale system usually follows a top-down path, i.e. the requirements are made at the higher level of the organization and then passed on to the lower levels of the organization[17], [18]. The complexity and association of various subsystems and levels in an organization of LSCES, the tendency of change in requirement induced in a complex system is high [14], [19]. The outcome of such change in requirement in different level increases the cost of LSCES, the cost of communication, the time of development and the value of the system[19].

In this thesis, Cynefin framework, sensemaking framework is used to capture the state of the system with respect to the different domains in the Cynefin framework when requirement creep occurs. The results from the study can be incorporated to understand the different rigorous approaches that the can be used for the design and development of a system when requirement creep occurs. The sensemaking framework can also be used as a predictive analysis tool which can help the decision maker analyze the past situations and create solutions for future. A distribution of discrete values of requirement creep is induced to find the change in cost and time of development. It is demonstrated by using a sample system decomposition on a hierarchical organization structure. The cost and time of communication within the levels of the sample hierarchy organization structure mimics the functioning of a real-time organization structure. A simple system and a complex system is used as a sample to make the decision maker understand the difference in the sensemaking framework for both ordered(simple) and unordered (complex) system. The uncertainty in the requirements are used to illustrate the change in state of the system with respect to the organizational preferences. Lastly, the design and development of the LSCES process is then mapped on to the Cynefin framework. This mapping is used to understand how the DM can use different rigorous systems engineering approaches during in the design and development of the LSCES. Uncertainty is then induced in the requirements creep and the results are mapped on sensemaking framework along with the variation in the cost and time. The different rigorous methods such as VDD and MDO are then mapped on to the Cynefin framework to help the designers understand the presence of ambiguity and uncertainty during the design and development of LSCES.

CHAPTER 2

BACKGROUND

Large-Scale Complex Engineered System

A system which is abundant in size, involving high complexity and interactions between many levels of people, organization, inter-disciplinary system is deemed as a Large-Scale Complex Engineered System (LSCES)[2], [20]. LSCES includes systems such as the aerospace systems and industry, larger maritime, major civil infrastructure systems, electric power grids and other large organizations[1], [21]. The development of LSCES take several years and are designed and operated by humans in day to day activities. Since the engineered systems are combined with humans, the system should be socio-technical in nature (i.e.) be self-aware of the system and surrounding [22]. The complexity of the LSCES revolves around the couplings with the sub systems, interdisciplinary systems and the size of the system and the socio-technical nature of the system. Hence the design and development of LSCES is associated with very high cost and high risk of failure [16], [23]. The most important factor during the design and development of a LSCES is avoidance of cost overrun and completing the project within the scope already allotted for it[6]. These challenges of design and development of LSCES are addressed by a discipline called as Systems Engineering (SE) which is used to capture the different interactions between the systems, sub systems and the interdisciplinary systems involved in a LSCES. Figure 3 is an example of a LSCES which consists of several satellites and their interaction with themselves and the ground station [24].

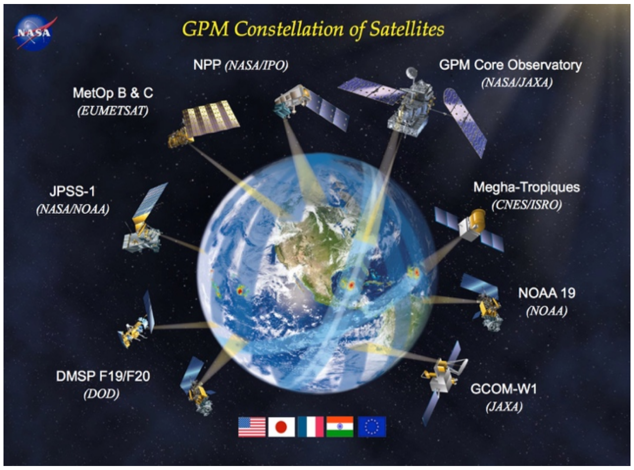

Figure 3. NASA GPM Constellation of Satellies [24]

System Engineering

The International Council on Systems Engineering (INCOSE) defines Systems Engineering as an interdisciplinary approach that enables the realization of successful system by concentrating stakeholders and customer needs early in the development cycle of the system using requirements in design synthesis and system validation [25], [26]. From the definition of Systems Engineering (SE) by INCOSE, it is inferred that presently systems engineering uses requirements elicitation to capture the needs of the stakeholders. These requirements are used in the design and development of LSCES to complete the specific design requirements. Requirements based systems engineering follow the 'Vee model' to capture the requirements, implement it in the design which is followed by testing, integrating, verifying and validating the system[3], [27]. The 'Vee Model' used in the systems engineering is provided in the Figure 4 below.

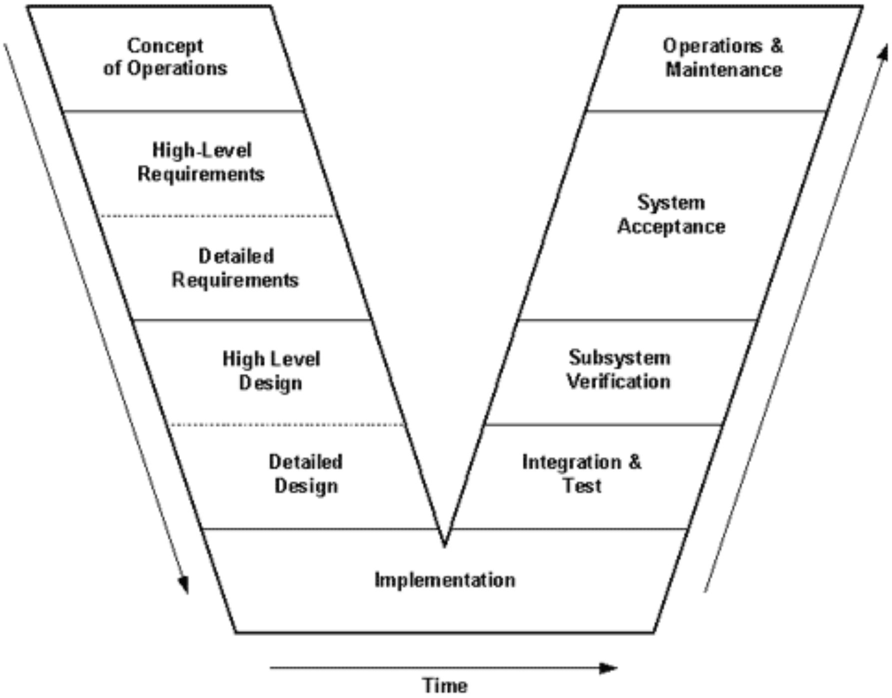

Figure 4. Vee Model of System Engineering [6]

Previous research on requirements based systems engineering reveals that requirements elicitation has numerous problems such as ill-defined requirements, ambiguity in requirements information, insufficient requirements from the customers and stakeholders, can lead to system not being developed appropriately[1], [11], [21]. Requirements when not captured correctly become a root cause for system failures, design failures which produces loss of revenue and time. It is also inferred that even when requirements are established properly, certain preferences of the customers are no captured properly and design is not what is intended by the customers[6], [28].

Past research by Mike Griffin has shown us that LSCES should have an elegant design by incorporating effectiveness, efficiency and robustness of a system and by reducing the number of unintended consequences[5]. To capture the loss in revenue, time and cost and to make the LSCES an elegant design, the preferences of the stakeholders which involves various disciplines are captured by using Decision Analysis, Multidisciplinary Design Optimization and Value driven design[8], [19], [29]–[32]. Due to the highly complex nature of LSCES and involvement of various people, these systems have inherent ambiguities and uncertainties linked to it. The ambiguities and uncertainties increase the cost and the time involved during the design of the LSCES. Ambiguities and Uncertainties of a system need to be resolved before the rigorous methods can be used to capture the preferences of the stakeholder.

Ambiguity

Ambiguity is ubiquitous to every field in our day to day life and it is being ambiguous about decisions. The definitions of ambiguity vary with the field it is used in. However, The general definition of ambiguity are given as follows "Having more than one possible interpretation or meaning, difficult to understand or classify; obscure[33][34]", "Missing information that is relevant and could be known"[35],"Ambiguity is defined as the availability of more than one qualitatively distinct interpretation" [36], "Ambiguity may be a component of complexity, where complexity involves social, technical, ethical, and organizational facets", "Absence of knowledge about functional variables"[35], [37].

Ambiguity is present in different fields and the definitions of ambiguity in a few fields are discussed. Ambiguity in art intends to give different interpretations visually. A highly ambiguous artwork gains more appreciation [38]. Ambiguity in language means doubtfulness or uncertainty of meaning or intention. There are two main types of ambiguity-Lexical ambiguity-multiple meanings for a single word, Syntactic ambiguity- the syntax of the sentence gives different meanings [39], [40]. In business Ambiguity deals with a situation which has more than one meaning causing confusion. Ambiguous situations can be defined as- completely new situations with no familiar cues or precedents, complex situations where a great number of cues and stakeholder interests to be considered, Situations which cannot be solved in usual way. Managers\leaders manage ambiguity by tolerating and managing the change effectively [41]. Ambiguity in military is intentionally used not to clarify the policies of the government or military. Such ambiguity is called Tactical ambiguity. Ambiguity was also used in the military vocabulary as VUCA which is volatility, uncertainty, complexity and Ambiguity. VUCA is used in emerging fields of strategic leadership and often relates to how people behave during decision making, planning and problem solving[42].

Decision making defines ambiguity as the when there is a lack of information but the description of the missing information is available. It is categorized under the term “unknown unknowns". It requires wide sources of information and hence the solutions got under ambiguity are well understood [43], [44]. In systems engineering theory management of ambiguities deals with approaches to cope with uncertainty in engineering systems. The ambiguity in the systems is managed by the implementation of flexibility and robustness. Lattice Analysis, Monte Carlo simulation framework has been used to implement flexibility in a large scale complex system[35], [37], [41], [45]–[50].

Uncertainty

Uncertainty is found in different fields from economics to engineering. Generally, uncertainty is defined as the condition of being uncertain, inability to predict the future. Uncertainty is the situation where the information is not enough for the problem to be solved. In systems engineering uncertainty is defined as the things that are known imprecisely [35], [41]. Uncertainty during problem solving is a situation in which the structure of the problem is given but the problem solver is dissatisfied with the knowledge of the value of the variables for the situation [35]. In systems engineering uncertainty is defined as the incompleteness in knowledge that causes model-based predictions differ from reality in a manner described by some distribution function[51]–[55].

During the development of LSCES, the requirements undergo many uncertainties and ambiguities which causes cost overrun and increment in time of development. To avert such cost overruns and increments during the development of LSCES, the operation of system should be understood. Sensemaking approaches can be used to understand the different processes involved in design and development of LSCES[53], [56], [57] after which the rigorous methods such as DA, MDO and VDD can be used to produce an elegant design for LSCES.

Decision Analysis

The design and development of LSCES requires decision making process to decide on factors such as stakeholder requirements, finance and economics involved, costs and risks, organization structures, methods of communication between the interdisciplinary systems and sub systems various other factors which affect the system or the subsystems. The theory of making choices under uncertainty which develop during the design phase constitutes the Decision Analysis [58], [59]. Decision Analysis is based on three theories- (I) Utility Theory (ii) Game Theory and (iii) Mechanism design. Utility Theory uses probability distribution of the outcomes of the uncertainty into a single value and is used when a single individual has uncertainties[59]. Utility theory can be normative – the study of how people should make decision or descriptive – the study of how people do make decision. Game theory is another method of decision analysis where multiple individuals are involved in making decisions. Game theory uses the strategies and the preferences of the individuals and then the decision are made. In engineering design, game theory is used when two or more designers design a system and while designing a new product. Mechanism design is the reverse of game theory, here the individuals are not informed of all the strategies and there is a gap of information, the decisions are made by making mechanisms[59]. Figure 5 shows the different risk preferences which an individual or an organization can have, depending on which the organizational preferences are determined by the decision makers in the organization[60].

Figure 5.Risk preference using Utility Function

Decision Analysis alone cannot capture the different preferences and the interactions between the different systems, sub systems within a LSCES. To find an elegant design for a LSCES with different design variables and complex couplings within the system optimization techniques need to be used. Since LSCES involves many interdisciplinary interactions within one another, Multidisciplinary optimization techniques are used to capture the preferences better [62].

Multidisciplinary Design Optimization

Optimization is a mathematical way of expressing the objective of a system and finding the optimum. The objective function consists of the design variables and alternatives help the designer they choose the best design [8]. Systems engineering approaches use Interface Control Documents (ICDs) to address interactions between the subsystems, which do not mathematically capture the physics-based coupling present in the system. Traditionally optimization is conducted separately for all disciplines involved in the system. The drawback in using traditional optimization is that the optimum design with respect to one specific discipline will not be same as optimum of other discipline of the same system[56], [61]. This challenge of traditional optimization is achieved through Multidisciplinary Design Optimization(MDO). The development of MDO began in the 1980s primarily to address the complexity of the system. It evolved from structural optimization and was established to enable optimization of the system by addressing the inherent interactions, couplings such that system consistency associated with physics can be achieved[62], [63]. MDO is used to capture the analysis of the system, optimization, the multiple objectives of the system and combine it to a single objective function. This objective function encompasses the objectives of the subsystems and the preferences of the stakeholders[8]. The couplings in the complex system can identified during the decomposition of the complex system[8], [31], [60], [64]. Figure 6 represents a coupled system which is the characteristic of a complex system. This system has 3 sub-systems, X's represent the design variables and the Y's represent the subsystem outputs.

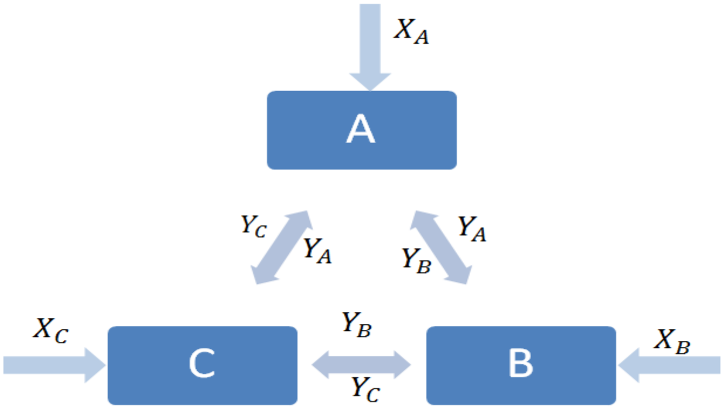

Figure 6. Coupled system for MDO

Value Driven Design

Value Driven Design (VDD) is an alternative system engineering approach, which addresses the economic based design methodology. VDD was developed because of incorporating the economic value model to enhance the use of MDO in systems engineering. It was established in the early 2000s to address the issues with communicating preferences of the stakeholders and the customers in the design and development of LSCES by using a single mathematical function called as the value function [65]–[67]. In VDD, a value function is created and flowed down the hierarchy of the system as opposed to requirements in the traditional SE approaches. VDD is used along with MDO by incorporating the design variables, the system configuration, attributes and the value in the value function represents the true preferences of the stakeholder by capturing the internal design trades through attributes [19], [32], [66], [68], [69]. The value function is formulated such that the attributes which define the system when decomposed from the top level of hierarchy satisfies the design of each subsystem. The preferences are captured and aligned to each level of the organization structure. The process of VDD formulation for a LSCES is shown in the Figure 6.

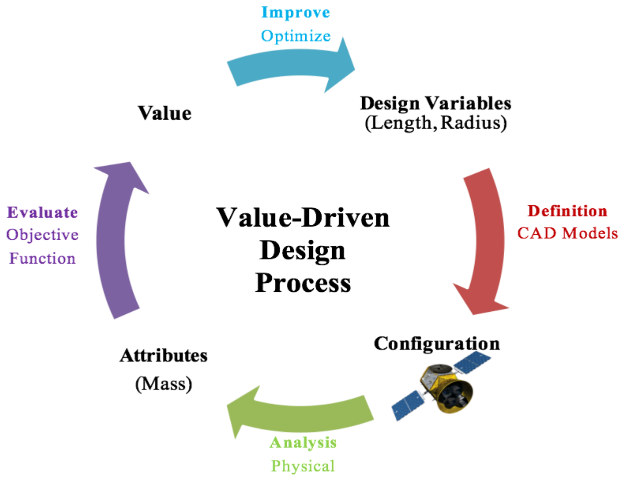

Figure 7. Value driven design approach to design LSCES

Sensemaking

Sensemaking is a social theory process of making sense of the situation. It can be used in understanding the current decisions and actions and used for future to take select best course of action. In other words, it is a process by which people give meaning to the experience. Karl. E. Wieck and Dervin are the two-main people who brought sensemaking to information science and organizational studies. According to Karl. E. Wieck, sensemaking is formulated in organizational structures to distinguish between uncertain situation due to ignorance and ambiguous situations due to lack of clarity and confusion [70]–[74]. Dervin's definition of sensemaking is the ability to gain clarity in ambiguous situations [75]–[78]. Sensemaking also helps in creating situational awareness and understanding situations of complexity and uncertainty during decision making. Klein refers to it to understand the connection between people, places and events [79]–[81].

Cynefin Framework

Cynefin is a welsh word and it means 'habitat' and Cynefin framework by Dave Snowden as a sensemaking framework to assist the decision makers. It uses knowledge management theory as a guide to differentiate between structured and unstructured conditions by using narratives. The relationship between humans, experience and the context is analyzed by this framework by proposing new approaches to decision making, communication and knowledge management. This framework is used not only for decisions made by leaders and managers but also in policy making, product development, market creation, and branding [12].

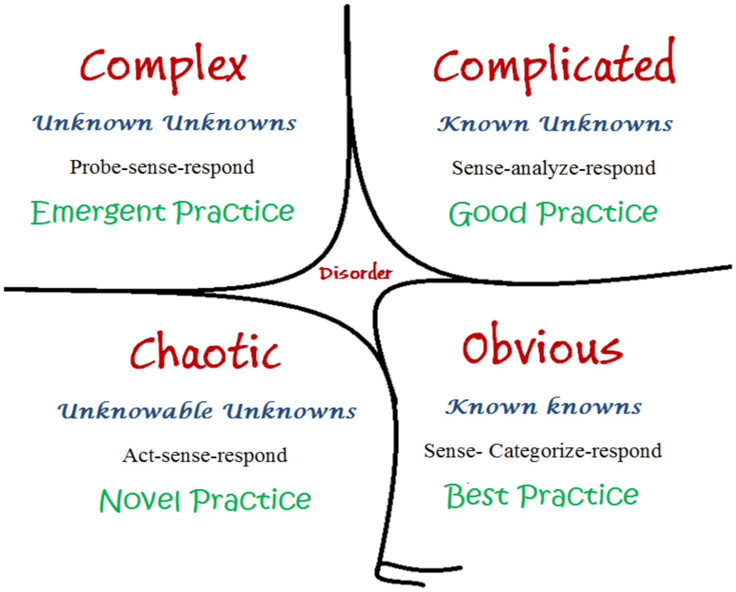

Figure 8. Cynefin Framework [82]

The Cynefin framework has five domains Obvious, Complicated, Complex, Chaotic and Disorder [82] as shown in the Figure 8. These domains in the Cynefin framework will aide in visualizing the different operations of the system in this thesis. These domains are used to categorize the problem or the system and assist the decision makers to provide better solutions. This framework was formulated to understand the world of ordered systems and unordered systems by providing different methods and tools for the decision maker. The ordered systems consist of the Obvious and complicated as the solutions can be easily discovered and the unordered system consists of the complicated and the chaotic region of the framework. The Figure 9 shows the state of our knowledge against the information available and this makes the decision maker easily spot the position of the system[83], [84].

		State of Available Information	
		Unknown	Known
State of our knowledge	Known	**Known Unknown** “The information is available and we have don’t have answers” (Know questions but no Solutions)	**Known Known** “The information is available and we have answers” (Know questions and Solutions)
	Unknown	**Unknown Unknown** “The information is not available and answers are not known” (Don’t know questions and Solutions)	**Unknowable Unknown** “The information we need is available somewhere but we don’t know how to find them” (Don’t know questions but know Solutions are available)

Figure 9. What do we know? - Knowledge Management [83]

The state of the knowledge with respect to known, knowable, unknowns and unknowable should be understood properly. These word in general have different meaning with respect to different fields. In this thesis, the word ‘Known’ describes is knowing the system, knowing the answer or solution for the DM and the word ‘Unknown’ describes the solutions not being available and not understanding the problem of the system.

The Obvious domain is characterized by clear cause and effect relationships and it is effortlessly understood by everyone. This region is termed as ‘Known knowns’ as the solutions to all the questions or problems are Known. This is the region where the managers undertake best practices. When the system or a person is at this region, sense-analyze-act are the steps that are essential to be taken [12], [82]. In systems engineering, when a system falls under this region, the system can use the solutions which are already provided. The uncertainty in this domain is very minimal and there is no trace of ambiguity as the solutions are clearly defined.

The next domain in the Cynefin framework is the complicated region. This region is determined by sense- analyze- respond and in the knowledge management as shown in Figure 9, it falls under the “Known Unknown” region as the solution can be found by analyzing the different results which are already available. When someone is at this stage of the Cynefin framework, expert’s opinion is one of the many ways to find the solution. Since the solutions can be determined with the help of expert opinions it is called as the domain of experts. This is the domain of "known unknowns" where the knowledge of the solution is known but the right answer is unknown[12], [82]. With respect to systems engineering, the uncertainty is in an unknown distribution of solutions. The decision maker(DM) can decide with respect to the previous data or expert’s opinion[85].

The complex domain and the chaotic domain comprises to form the unordered region in the Cynefin framework. The complex domain is the domain of the emergence, it is domain where the manager’s probe - sense – respond as the right solutions cannot be determined directly for a problem. The cause and effect of the problem is very unclear and the solutions are to be predicted by probing or emerging from a set of solutions. In the knowledge management diagram, the complex region falls under the “Unknown Unknown” region[12], [13], [83]–[85]. The chaotic domain is the region where the managers go momentarily when any crisis occurs because staying at the region for long time would result in the failure. Hence this region asks the managers or the DM’s to act-sense-respond. The first step of the decision maker would be to act and bring the system in control and then move the system to other domains of the Cynefin framework. There is no cause and effect relationship and this domain is the when the system is under crisis. Innovative ideas are used to find the answers and this is the domain of "Unknowable Unknowns"[12], [13], [83]–[85].

The fifth domain is the domain of disorder. This domain is when the system does not fall in any of the categories mentioned above. Disorder is the region to gather info, identify the domain in the Cynefin Framework and move on. The system would eventually be moved to any of the domains by breaking them and them putting the pieces into the relevant domains of the Cynefin framework. This movement between the different domains of the Cynefin framework is defined by the Cynefin Dynamics.

Cynefin Dynamics

Cynefin Dynamics deals with movement of the problem or system between the different regions of the Cynefin framework by understanding different movements that are possible within the Cynefin framework. The movements within the Cynefin framework are found to be between the different boundaries such as the known (Obvious) - chaos boundary, known (Obvious) – knowable (complicated) boundary, knowable (complicated) - complex boundary, complex - chaotic boundary and visiting chaos[13], [83]–[87].

The movements between the different domains of the Cynefin framework is provided in the Figure 10. The movement of the system within the known and chaos boundary is the strongest and the most dangerous. The boundary between the Obvious state and chaotic stage is a cliff and falling from Obvious state to chaotic stage can be fatal for the system if not recovered in time and it is termed as the asymmetric collapse and movement from chaos to Obvious is known as imposition. The movement between the known region and unknown region is determined to be the incremental improvement as cyclic information is required for growing using expert’s advice. The movement between the complicated and the complex region is the region where just in time and exploration occurs[13], [83]–[87].

Exploration opens possibilities and Just-in-time is exploitation which narrow down the possibilities. The movement from chaos to complicated via complex is called swarming. This shows how the solutions can be found from exploration, and exploitation when the system falls under chaos. The movement from complex to chaotic and back is termed as Divergence – Convergence. This movement of the system between the two regions tends to create a rich variety and provide a lot of information can help in facilitating sensemaking of ambiguity and uncertainty in the two regions. The dynamics of visiting chaotic region deliberately is used as stimulant for new growth. Entertainment breaking, Liberation and Immunization are the three different types of dynamics which visit chaos deliberately. These movements between the boundaries are taken as the base for the position of the different stages of design and development of LSCES.

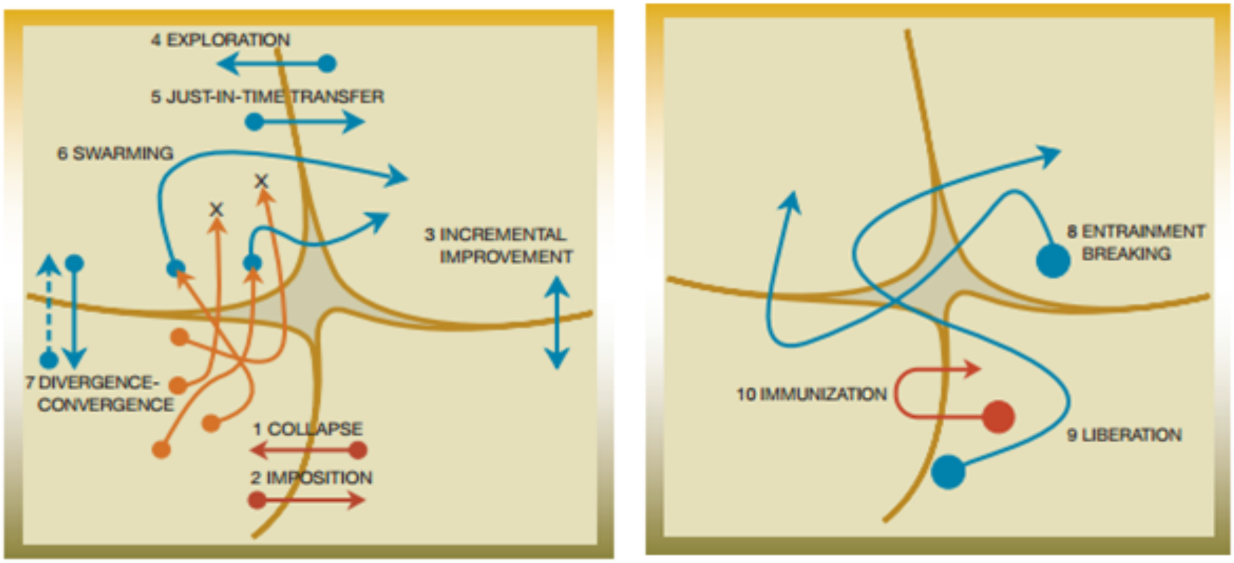

Figure 10. Cynefin Dynamics[13]

In case of any system, when there is a change in the form of creep or disturbance in the form of noise, the system first goes into chaotic region where the decision maker needs to take quick action to get out of disaster [13], [83]–[87]. Once the system is stable, it is moved to the region of disorder as the state of the system is not known, such that the decision maker needs to sense and analyze with the information available to him. In this thesis, Cynefin framework is combined with VDD and MDO in the organization structure of the LSCES to understand the state of the system during the requirements creep at various levels in the organization and be used as predictive analysis tool. The Cynefin framework will also be used in the design and development of LSCES.

CHAPTER 3

RESEARCH QUESTIONS

This chapter describes the research questions, which were formed to understand the sensemaking process and its utilization in the development of Large Scale Complex engineering system.

Research Question 1

"Can the use of Cynefin framework, sensemaking framework aid in the design and development process of the Large-Scale Complex Engineered Systems by using traditional requirements driven systems engineering process?"

This research question will be addressed by creating a simulation of hierarchical organization of a system. A Simple and Complex system will be modelled on the same hierarchical organization. A set of requirements are provided to both simple and complex system. Then the requirements are altered to produce requirement creep, which deters the state of the system and increases the time and cost of the system. The state of the system will then be identified by using the sensemaking framework, Cynefin framework so that the decision makers can understand the measures needed to stop the system from failing. The Cynefin dynamics will be used to understand the movement of the system in Cynefin framework.

Research Question 2

"How does Cynefin framework capture change in the state of the system due to the organizational preferences to address uncertainty in requirements and aid in the decision making of the system?"

This research question will be discussed by inducing uncertainty into the requirements of the LSCES. Simple and complex system with same hierarchical organization structure will be used to address this research question. Organizational preferences will be used to understand and eliminate the situation when cost and time required to satisfy the requirements creep produced is within the organizational preferences. There may be change in the state of system with the organizational preferences and this can be used to improve decision making process during the design and development of LSCES.

Research Question 3

"Can the sensemaking framework be used as an analysis tool to resolve uncertainty and ambiguity and identify the different rigorous approaches of Systems Engineering, that can be used during the different phases of design and development of Large Scale Complex Engineering Systems?"

This research question will be addressed by first understanding the basics of sensemaking framework, the Cynefin framework on the design and development of LSCES. The uncertainty and ambiguity are mapped on to the Cynefin framework by using the knowledge that will be available. Using the knowledge needed for the rigorous approaches such as Decision Analysis(DA), Value - Based approaches like Value Driven Design (VDD) , Multidisciplinary Design Optimization (MDO) ,the approaches are mapped on to the Cynefin framework. The different stages of design and development of the large-scale systems will be identified related to different approaches by making sense of the stage using the Cynefin framework. This is then mapped to the Cynefin framework using the Cynefin dynamics to determine the rigorous approaches can be used when the system is at the specific region of the Cynefin framework during the design and development phase.

Organization of Thesis

The Chapters 1 and 2 provide an overview of how sensemaking can be used during the design and development of LSCES and the motivation behind the research and addressed the research questions for this thesis. Chapter 3 will provide the necessary background to understand the different topics which are related to the thesis. Chapter 4 will describe the organization model used to demonstrate the Cynefin framework-sensemaking framework in thesis. Chapter 5 will provide the state of the system when requirement creep occurs by using Cynefin framework and its dynamics. Chapter 6 will provide the results and discussion of effect of uncertainty using Cynefin dynamics on the different requirement creep and Chapter 7 will deal with the different approaches that can be used to improve the design and development of LSCES. Chapter 8 will provide the summary, conclusion and future work.

CHAPTER 4

DETERMINISTIC ORGANIZATION MODEL

In any industrial organization or any large-scale company, the organizational structure deals with the activities, task allocation, co-ordination and supervision of all the activities within the organization[15]. It also determines the role, power, responsibilities and the information flow between the different levels of management. The organization structure is classified depending on size, location, products and various other factors [88] . Depending on the nature of communication between the different levels, the organization structure can be classified as hierarchical, matrix type; functional type [89], [90]. These organization structure design are used in the design of LSCES by using the value function of the complex systems. The organization structure of LSCES consists of various objectives which needs to be captured and this is performed by using optimization[14], [19], [68].

In this thesis, a hierarchy organization structure is used to demonstrate the use of Cynefin framework- sensemaking framework in the design and development of LSCES. This model is used to address the first two research questions of the thesis. The requirement creep is induced the organization and the state of the system with respect to the creep and the system is also demonstrated. The hierarchical organization structure follows the layout of a pyramid and every sub-entity is connected to other entity. The communication in this type of organization is simple and has only two ways of communication from top down or bottom up[15], [16].

The organization structure used as a test case in this thesis consists of 7 levels with several sub-systems in each level. The hierarchy organization structure along with the respective subsystems in shown in the Figure 11. This organization model is assumed to accommodate different physical system. The physics of an engineered system can either be simple or complex depending on the couplings, attributes and the complexity of the system [8].

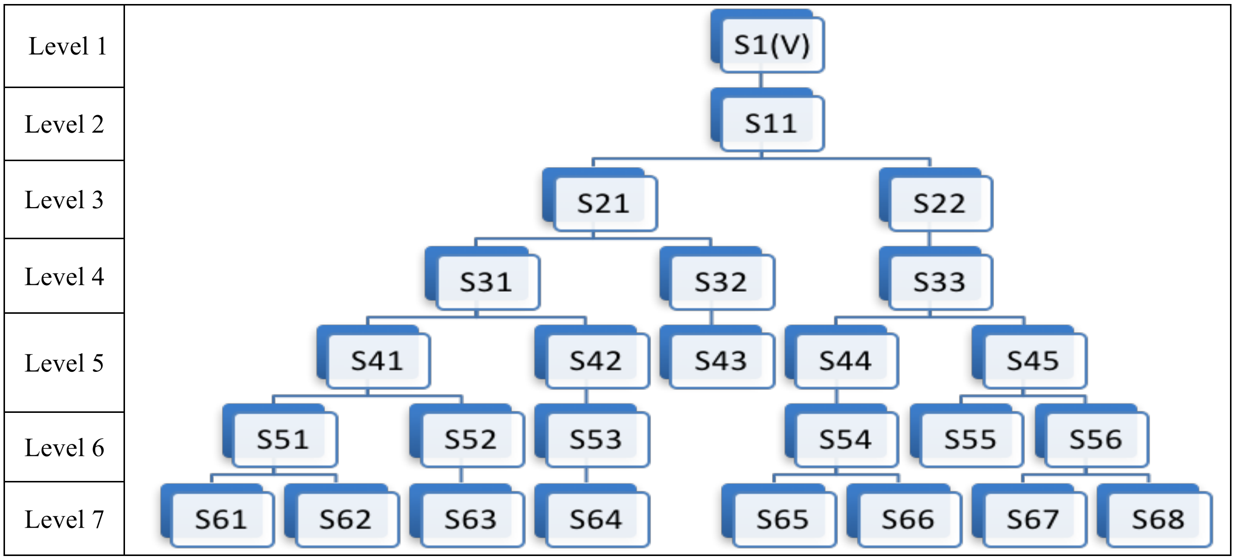

Figure 11. Hierarchical Organizational Structure of System

A simple system is characterized by direct interactions between the sub systems and are highly organized and is highly predictable. A complex system is characterized by indirect interactions between the sub systems and have several elements and couplings within the subsystems[91]. A simple system (ordered system) will enable the decision makers to understand the working of sensemaking framework easier before it can be used in a complex system (unordered system) [12]. To understand the differences of the working of the Cynefin framework, both simple system and complex system are used in this thesis.

In this thesis, the simple and the complex system consists of 7 levels and 25 sub-systems which are shown in the Figure 11. The mass of the system is considered to illustrate the working of Cynefin framework in the thesis. An arbitrary mass requirement is decomposed from the top level of the hierarchy to the bottom level in the hierarchical organization structure for simple and complex system. The mass value of the overall system is then decomposed to every subsystem in a top-down approach. The simple system consists of 25 attributes and 36 design variables and the complex system consists of 25 attributes and 31 design variables. The mass value of simple system is provided by Eq. (1).

$$\boldsymbol{V = X_{011} * X_{012} * X_{013} + A_{111}^{2}} \qquad \textbf{Eq. (1)}$$

The equations to find the mass of all the other sub - levels for the simple system are provided in Appendix I. The attributes are represented as A_{abc} and the design variables are given as X_{abc}, where the subscripts 'a' denotes the level, 'b' the sub-system and 'c' represents the equation position of the attribute or design variable in the system.

Likewise, for the complex system, the mass value of the overall system is given by the Eq. (2). Normally a complex system is considered to have couplings and so in this thesis, the system is considered to have 5 coupling. The equations of the other entire sub - levels for the simple system are provided in Appendix II.

$$\boldsymbol{V = A_{111} + X_{011} + \frac{A_{421}}{5}} \qquad \textbf{Eq. (2)}$$

The value of the complex system is given by the equation (2) of the paper. The complex system has many couplings and in this paper 5 attributes that are coupled are $A_{211}, A_{311}, A_{331}, A_{441}, \& A_{671}$. The attributes used for the complex system are provided in Appendix II of the paper.

Organizational communication is an important factor in any organization structure during the development of a system. It involves a lot of interactions and exchange of information between different organizational levels[14]. These communications are associated with a cost and time within the organization. To mimic these communications between the organizational levels, a cost a time as shown in the Table 1 are used to design the hierarchical organization for both simple system and complex system. The numbers used in the table are arbitrary for the deterministic model.

Table 1. Organizational Level Values for Sample System

Organization Parameter	Unit Cost	Unit Task Duration (Weeks)
System Level (Level 1)	1.0	0.50
Level 2	1.5	1.25
Level 3	1.25	1.25
Level 4	1.75	0.75
Level 5	2.0	1.5
Level 6	1.0	1.25
Level 7	1.0	0.50

The cost and time of communication between the different levels of the organization structure is used during the breakdown of the mass from the top level of the system to sub-levels in the organization structure. Each subsystem has its own cost and time associated with it. These are used to measure the time and cost involved during the interactions within the organization. The total cost of the system includes cost of the system or the sub system of the organization and the cost of communication between the different levels of the organization as shown in the equation 3, 4, 5 and 6.

$$Cost_{org} = Cost_{sys} + Cost_{int} \qquad \textbf{Eq. (3)}$$

$$Cost_{sys} = \sum_{i=1}^{n} Cost\ of\ sys_{levels} \qquad \textbf{Eq. (4)}$$

$$where\ n\ is\ the\ number\ of\ levels$$

$$Cost\ of\ sys_{levels} = Cost\ of\ sys + \sum_{i=1}^{j} Cost\ of\ subsys_{levels} \qquad \textbf{Eq. (5)}$$

$$where\ j\ is\ the\ number\ of\ sub\ systems\ in\ a\ level$$

$$Cost_{int} = \sum_{i=1}^{n} Cost\ of\ interaction_{sys}$$ **Eq. (6)**

$$where\ n\ is\ the\ number\ of\ levels$$

The time of development of the system and interaction between the system and the sub levels of the organization are provided in the equations 7, 8 , 9 and 10 below. The total time of the system is calculated by adding the Time of development of the system and time of interaction as shown in Eq. (7).

$$Time_{org} = Time_{sys} + Time_{int}$$ **Eq. (7)**

$$Time_{sys} = \sum_{i=1}^{n} Time\ of\ sys_{levels}$$ **Eq. (8)**

$$where\ n\ is\ the\ number\ of\ levels$$

$$Time\ of\ sys_{levels} = \ Time\ of\ sys + \sum_{i=1}^{j} Time\ of\ subsys_{levels}$$ **Eq. (9)**

$$where\ j\ is\ the\ number\ of\ sub\ systems\ in\ a\ level$$

$$Time_{int} = \sum_{i=1}^{n} Time\ of\ interaction_{sys}$$ **Eq. (11)**

$$where\ n\ is\ the\ number\ of\ levels$$

Hence, the design and development of a system also includes the cost and time of development of the sub systems. In this thesis, for both simple and complex system, the cost and time of development is provided in the Appendix A and Appendix B. These values are included to demonstrate the use of Cynefin framework in the Large-Scale Complex Engineered System. This hierarchical organization is used to demonstrate the requirements creep by changing the requirements and the sensemaking framework is used to capture the state of the system and aid the decision maker to make better decisions. This is demonstrated in the Chapter 5 of the thesis.

CHAPTER 5

SENSEMAKING IN LSCES DUE TO REQUIREMENTS CREEP

Sensemaking, as the word suggests means making sense of the past actions to take better decisions for the future [12], [73], [83]. Past researches have shown that during the design and development of LSCES, a large amount of creep occurs due to requirements and this in turn increases the cost and time of development of the system[68]. To address the requirement creep and to understand the functioning of sensemaking framework, the hierarchical organization provided in the previous chapter is used to demonstrate the purpose of sensemaking.

In this chapter, Cynefin framework is used illustrate the idea of using sensemaking in the systems engineering in the event of requirement creep which address the Research Question 1 mentioned in the Chapter 3 of the thesis. The requirement creep is indicated by using a proxy that represents the mass of system, which is a typical requirement imposed on large complex systems. For example, when the mass of a satellite system is decomposed, the mass is decomposed to different sub systems and the interdisciplinary systems involved in it. An arbitrary mass requirement is decomposed from the top level to the bottom level in the hierarchy structure. The requirement creep is then induced in the system by changing the requirement at different levels of the organization structure.

Typically, at any instance before the requirement creep the state of system is constant but it changes at the event of requirement creep. The change in the state of the system can captured by the Cynefin framework by the Cynefin dynamics and this helps the decision makers to understand the state of the system. Both Simple and Complex system are used to illustrate the change in state of the system at the event of requirement creep to generate a general idea on how the sensemaking framework can be used in Systems Engineering.

The mass distribution within a system can be allotted with regards to prior information, for example it is known the if the total mass of the satellite system is allotted to be 20000Kg, the payload will be 20% of the total mass, fuel as 18% and so on. In the same manner, the mass requirement is made for both simple and complex system for the same hierarchical organization structure. To show the creep in requirement, the initial requirements are allotted to the system in an orderly fashion following a top down approach. The mass requirement for simple system and complex system used in the thesis is shown in the Tables 2 and 3 respectively.

Table 2. Requirement values for Simple System

Level	Simple System
Level 1	1120
Level 2	1050
Level 3	1025
Level 4	1000
Level 5	975
Level 6	900
Level 7	150

Table 3. Requirement values for Complex System

Level	Complex System
Level 1	180
Level 2	170
Level 3	160
Level 4	150
Level 5	145
Level 6	100
Level 7	60

Initially, at any given time the system lies in the Obvious region of the Cynefin framework where the system functions normally without any issues. The requirement creep is then induced into the system at different levels of the organization and the change in the state of the system is captured. The state of the system changes from Obvious, complicated, complex, chaotic and disorder depending on the change in requirement. The movement of the system from one region of the Cynefin framework to another is captured by the Cynefin dynamics. The Cynefin framework assists the decision makers to provide solutions such that the system gets back to the Obvious region of the framework.

Case Study 1: Requirement Creep in Simple System

First, the simple system is used to illustrate the requirement creep by changing the requirements at different levels of the organization. The requirement provided to the level 1 of the system is 1120 and this is found in the Table 4. The requirement of the level 1 is changed from 1120 to 1110, there by creating a creep. This change in requirement needs to be communicated to the lower levels of the system. It is understood that the system when functioning normally, the state of the system is in the Obvious region of the Cynefin framework. When the requirement creep occurs in level 1, it is seen that the system's normal functioning is changed and the state of system changes to chaotic because of the sudden disturbance. Due to the nature of chaotic region, the decision maker needs to take an action. In this case, the decision maker knows the mass distribution method of the entire system and knows that he needs to assign new values to the lower level. The state of knowledge of the decision maker is known known. This is because he knows what is going and what action must be taken and so the system moves to the region on known knowns, which is the Obvious region. The movement of the state of the system is shown in the Figure 12.

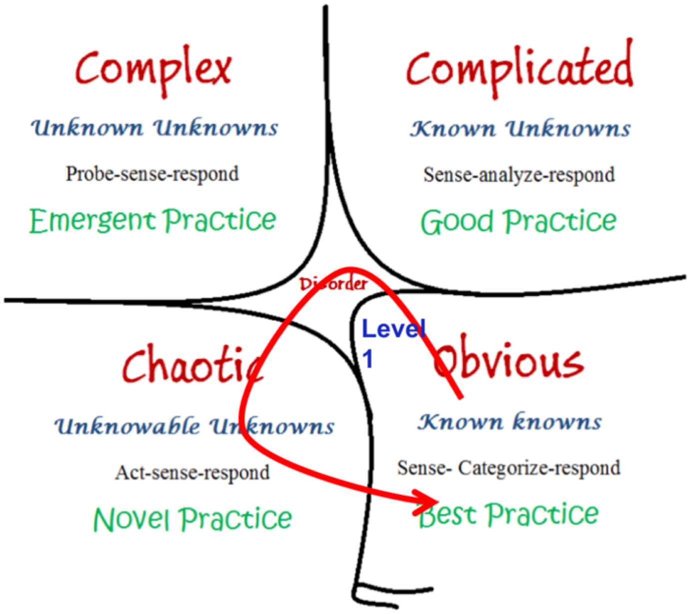

Figure 12. Simple System -Movement of the State of the System during requirement creep in Level 1

The Figure 12 shows the movement of the simple system from Obvious→ Chaotic→ Disorder → Obvious for a requirement at level 1 of the organization structure. Changes are made to the design variables such that the requirement is reduced but it equals to the new value provided. This change requirement also produces a change in the cost and time of development of the system. The cost and time of the system before the requirement creep and after the requirement creep for level 1 is shown in the Table 4.

Table 4. Simple System - Requirement creep in Level 1

Level 1 (Simple System)	**Initial Requirement 1120**		**Changed Requirement 1110**	
	Cost	Time	Cost	Time
System	32.63	23	1068.8	720
Co-ordination	8.75	6.75	217.50	292.50
Total	**41.38**	**29.75**	**1286.3**	**1012.5**

From the Table 4 it is observed that a small change in the requirement can produce a large amount of change in the cost and time of the system. From the above Figure, it is also noticed that the Cynefin dynamics is like immunization but as in this case the system is not voluntarily placed in the framework. It goes from Obvious → Chaotic which is the collapse of the system after which system is brought back to the Obvious state.

Next the requirement is changed in level 2 of the organization structure to 1040, the state of the system changes from Obvious to chaos momentarily before the decision maker takes an action. At the chaotic region, the decision maker takes quick action of moving the system from chaos to disorder, a state where the decision maker is unsure of where the system would lie. Since the system is a simple system, the decision maker senses and analyses that the requirement needs communication to level 1 above and other levels below. It needs expert's advice from all the levels and the interactions between the levels can provide and answer. The state of knowledge of decision maker is known unknown, as he knows that he requires expert's advice but he does know what new values needs to assign to other levels of the organization structure. Hence the state of the system moves from chaotic to complicated as shown in the Figure[fig].

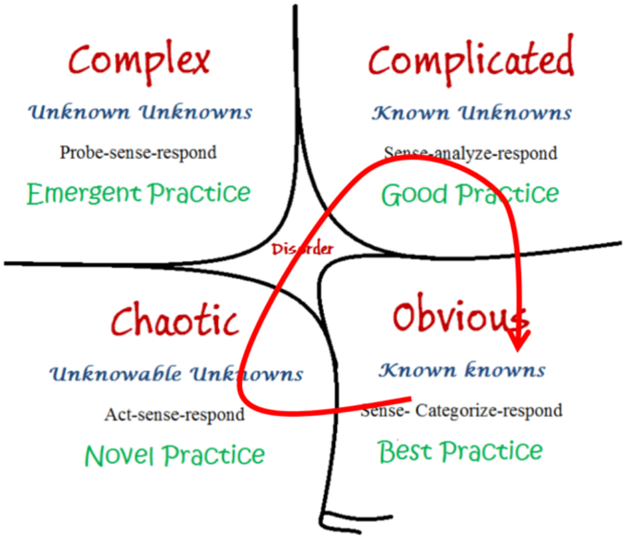

Figure 13. Simple System - Movement of the State of the System during requirement creep in Level 2

The Figure shows that the state of system moves from Obvious→ Chaotic→ Disorder→Complicated → Obvious. The movement represents swarming motion of Cynefin dynamics, moving from the Obvious to chaos then to complicated and back to Obvious. The change in cost and time associated with the change in requirement at this level is shown in the Table 5. The state of the system when in the chaotic region needs immediate action, this is cause the system may go into the failure mode if it is in the chaotic regime for a long time. Since the DM knows where the solutions lie but does not know the solution, the system goes through complicated stage.

Table 5. Simple System - Requirement creep in Level 2

Level 2 (Simple System)	**Initial Requirement 1050**		**Changed Requirement 1040**	
	Cost	Time	Cost	Time
System	32.63	23	37.625	25.5
Co-ordination	8.75	6.75	11.25	8.5
Total	**41.38**	**29.75**	**48.875**	**34**

The requirement in the 3rd level of organization is changed to understand the change in the state of the system. The system which is normally in the Obvious state of the Cynefin framework moves to the chaotic region. The decision maker makes quick action to remove the system from the chaotic region by moving it to the disorder state where the state of the system is unknown. Here the decision maker senses a change in the third level and knows that the solution can be found by direct interaction between the levels 2, level 1. The problem is known that there is change in the requirement in level 3 and decision maker needs to find the solution which is unknown within the levels. Since the system is under known unknown state, it falls in the complicated stage of the Cynefin framework. Just like level 2, the state of the system moves from Obvious→ Chaotic→

Disorder→Complicated → Obvious as shown in the Figure 13. It is also recognized from the level 2 that when the change occurs in requirement, it causes a change in the cost and time of system thus changing the value of the system as shown in the Table 6.

Table 6. Simple System - Requirement creep in Level 3

Level 3 (Simple System)	**Initial Requirement 1025**		**Changed Requirement 1005**	
	Cost	Time	Cost	Time
System	32.63	23	45.125	28
Co-ordination	8.75	6.75	12.5	9.75
Total	**41.38**	**29.75**	**57.625**	**37.5**

The requirement in 4th level is altered from 1000 to 990, to see that the state of the system changes from Obvious to chaotic. It has already been described that the system is simple and it has direct interactions between the different levels of the organization. So, it is observed just like level 2 and 3, the state of the system moves from Obvious→ chaotic→disorder→ complicated → Obvious. The disorder stage can be avoided once the decision maker knows which system the change has occurred. The change in value of the system due to presence of the requirement creep is shown in the Table 7.

Table 7 . Simple System - Requirement creep in Level 4

Level 4 (Simple System)	**Initial Requirement 1000**		**Changed Requirement 980**	
	Cost	Time	Cost	Time
System	32.63	23	48.875	30.25
Co-ordination	8.75	6.75	14.25	10.5
Total	**41.38**	**29.75**	**63.125**	**40.75**

It is observed that when the requirement creep is induced in the next levels of 5, 6 and 7, the state of system behaved in the same way as that of the level 2,3 and 4. The state of the system changed from Obvious to chaotic and then it moved to complicated and then back to Obvious. This is because of nature of the system and the communications within the organizational structure which is direct. The state of the system may have gone to complex region of the Cynefin framework if the system had indirect communication thereby increasing the complexity of decision making. The change in cost and time regarding the requirement creep of levels 5,6 and 7 are provided in the Table 8, Table 9 and Table 10 respectively.

Table 8. Simple System -Requirement creep in Level 5

Level 5 (Simple System)	**Initial Requirement 975**		**Changed Requirement 945**	
	Cost	Time	Cost	Time
System	32.625	23	112.75	72
Co-ordination	8.75	6.75	31	23.5
Total	**41.38**	**29.75**	**143.75**	**95.5**

Table 9. Simple System - Requirement creep in Level 6

Level 6 (Simple System)	**Initial Requirement 900**		**Changed Requirement 850**	
	Cost	Time	Cost	Time
System	32.625	23	123.75	79
Co-ordination	8.75	6.75	33	26
Total	**41.38**	**29.75**	**156.75**	**105**

Table 10. Simple System - Requirement creep in Level 7

Level 7 (Simple System)	**Initial Requirement 150**		**Changed Requirement 130**	
	Cost	Time	Cost	Time
System	32.63	23	65.25	46

Table 10 Continued.

Co-ordination	**8.75**	**6.75**	**17.59**	**13.50**
Total	**41.38**	**29.75**	**82.84**	**59.5**

From case 1, it is observed that for a simple system with hierarchical organization structure the requirement creep changes the state of system from Obvious to chaotic and complicated and then back to Obvious. The problem is known and the solution is unknown and hence it would fall in the complicated region of the Cynefin framework. The movement of the state of the system for different levels in a simple system through the Cynefin framework is present in the Figure 14 for level 1 and Figure 15 for other levels.

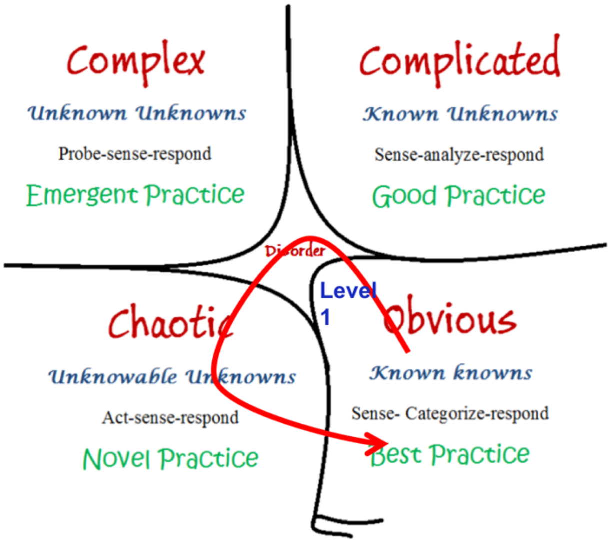

Figure 14. Movement of State of System in Level 1 for Simple System

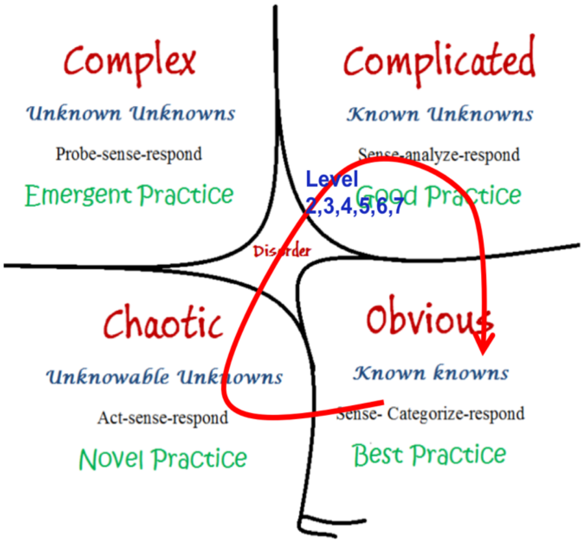

Figure 15. Movement of State if system in Level 2,3,4,5,6 &7 for Simple System

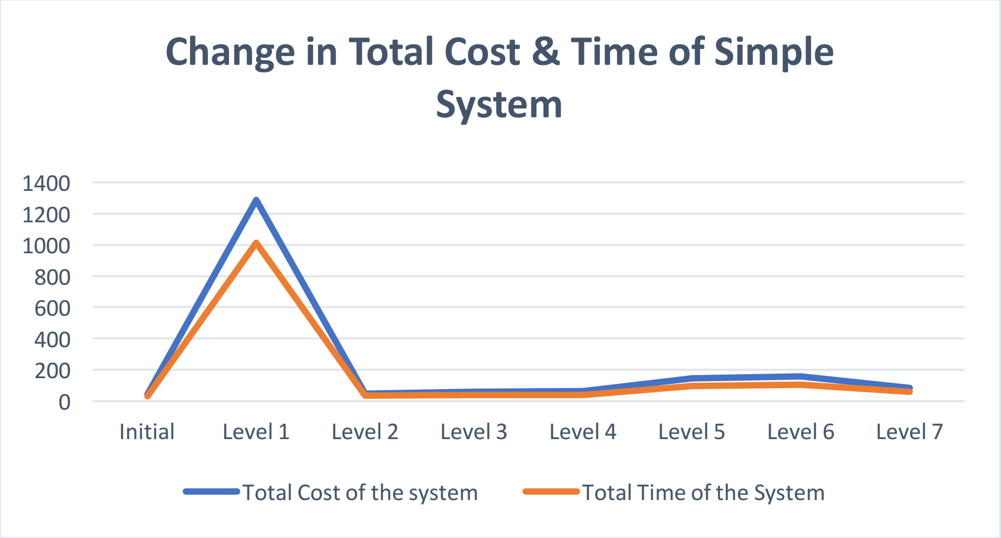

Figure 16 . Change in cost and time with respect to requirement creep in Simple System

From the Figure 16, it is observed that the level 2 has a spike in the distribution of the cost and time. This shows the time and cost involved in translating the requirements and from level two is higher than that of other levels. This can also be linked to the falling of the system from Obvious stage of the framework to the chaotic stage being fatal before moving back to other regions. It is also inferred that requirement creep of level 3,4,5,6 increases steadily and the cost of level seven is lower. The cost and time of the requirement creep of seventh level being lower can be because of deterministic organization design.

Case Study 2: Requirement Creep in Complex System

An unordered or a complex system is used in the next part of the study. A system is presumed to be complex system in the presence of the couplings. A coupling is nothing but an interdependency in the system and in this case study, the complex system has 5 coupling between the sub systems in the level 2, 3, 4 and 6. When the requirement creep is induced in the system, couplings between different levels makes it tough for the DM to understand the system and find the solution. Even though the system is complex, the state of the system when functioning normally is Obvious as the system lies in the Known Known region of the Cynefin framework.

The requirement creep is first induced in the system in level 1. It causes a disturbance in the state of the system, as the reason for the disturbance is unknown, and the system is moved to the chaotic region. The temporary position of the system at the chaotic region is changed once the DM understand the problem. In this instance, the requirement creep is at level 1 of the system as the requirement is reduced by 10. Since the physics of the system is complex, the DM knows that the change in requirement just needs to be broken down to the different levels of the system. Hence the problem is known but how much of a change will be impacted to other levels is not known and so the system falls in the known unknown state, which is the complicated region of the Cynefin framework. The movement of the system is from Obvious→ Chaotic→ Disorder → Complicated → Obvious and this is shown in the Figure 17.

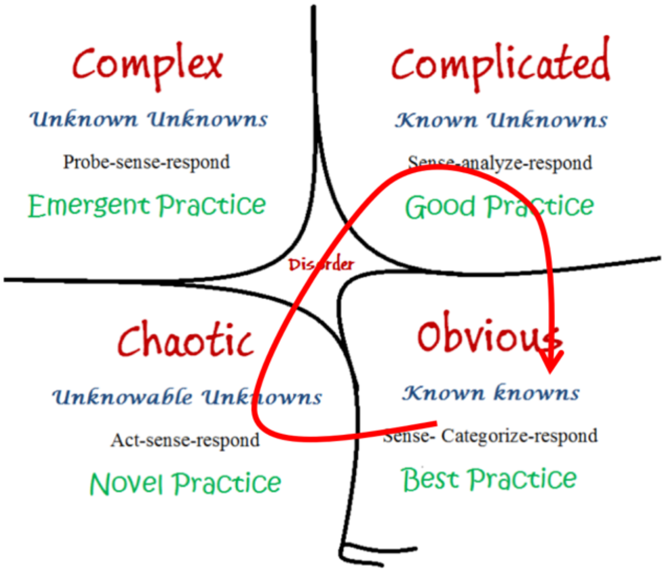

Figure 17. Complex System - Movement of the State of the System during requirement creep in Level 1

The cost and time for the system during development is found to be 40.37 and 29.5, but after the requirement creep occurs it changes and is increased to 887.5 and 621. This is because of the communication between the different levels and the cost and time associated with the sub-systems in different levels. The change in cost and time is shown in the Table 11.

Table 11. Complex System - Requirement creep in Level 1

Level 1 (Complex System)	**Initial Requirement 180**		**Changed Requirement 170**	
	Cost	Time	Cost	Time
System	31.62	22.8	692.5	476
Co-ordination	8.75	6.75	195	145
Total	**40.37**	**29.55**	**887.5**	**621**

The requirement in level 2 is changed to understand the difference when compared to requirement creep of level 1 in a complex system. During this event system moves from Obvious to chaotic region when the creep occurs. As the DM takes quick actions at this state, the system moves to the chaotic region shortly. DM knows that system is complex and knows that level 2 has a coupling between level 4 but he does not know where the solution lies. He needs to probe to find out the solution. Hence, the system moves to the complex domain, where the DM needs to probe, sense and then act. Once the DM understands the location of the solution, he needs to go through communications between the different levels to get the solution. Expert's advice is required and therefore the state of the system moves from complex to complicated and back to Obvious. This movement of the state of the system is represented in the Figure 18.

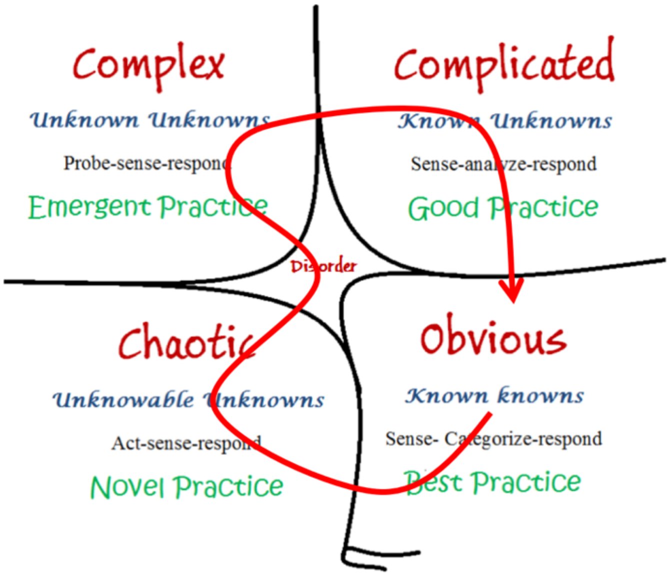

Figure 18. Complex System - Movement of the State of the System during requirement creep in Level 2

From the Figure, it is observed that the system moves from Obvious → Chaotic → Disorder → Complex → Complicated → Obvious. The change in cost and time with respect to the change is requirement creep is shown in the Table 12.

Table 12. Complex System - Requirement creep in Level 2

Level 2 (Complex System)	**Initial Requirement 170**		**Changed Requirement 160**	
	Cost	Time	Cost	Time
System	31.62	22.8	549.375	379.5
Co-ordination	8.75	6.75	168.75	127.5
Total	**40.37**	**29.55**	**718.125**	**507**

From the above Table, it is inferred that as the system moves from one state to another, the cost and time of system increases along with the cost of interaction between the systems. When the requirement is changed in the other levels such as level 3 to level 7, the same movement of the system is observed. The system moves from Obvious to chaotic then to complex-complicated and back to Obvious. This is similar the swarming movement in the Cynefin dynamics. It is the transitioning of the system from an unordered state to ordered state. This does not change the physics involved in the system, it only aides the DM to find solutions and make decision easier. The movement of the state of the systems during the requirement creep of the levels are shown in the Figure19 for level 1 and Figure 20 shows the movement of the systems in other levels of the Complex System.

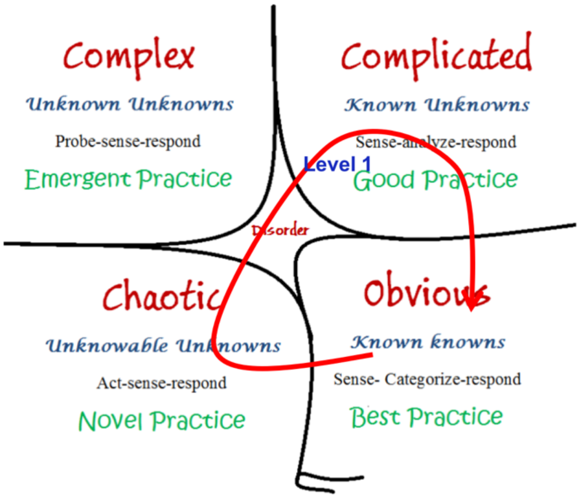

Figure 19. Movement of State of System in Level 1 for Complex System

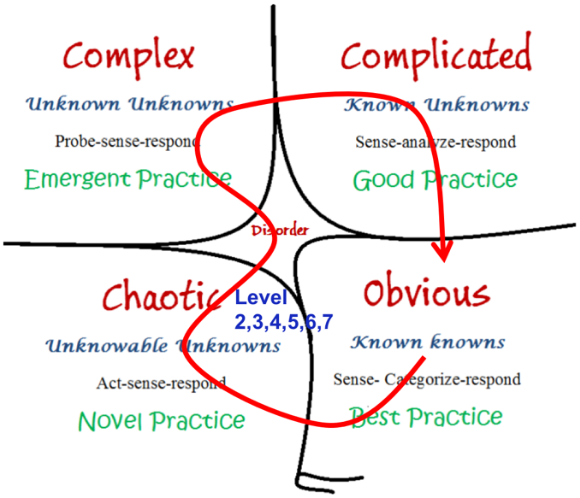

Figure 20. Movement of State of System in Level 2,3,4,5,6,7 for Complex System

The cost and time of the system and the co-ordination involved due the changes in requirements the other levels from level 3 to level 7 are provided in the Tables 13, 14, 15, 16 and Table 17.

Table 13. Complex System - Requirement creep in Level 3

Level 3 (Complex System)	**Initial Requirement 160**		**Changed Requirement 150**	
	Cost	Time	Cost	Time
System	31.62	22.8	573.625	361.40

Table 13 Continued.

Co-ordination	8.75	6.75	361.40	126.75
Total	**40.37**	**29.55**	**935.025**	**488.15**

Table 14. Complex System - Requirement creep in Level 4

Level 4 (Complex System)	**Initial Requirement 150**		**Changed Requirement 145**	
	Cost	Time	Cost	Time
System	31.62	22.8	861.75	540.90
Co-ordination	8.75	6.75	256.5	189
Total	**40.37**	**29.55**	**1118.25**	**729.9**

Table 15. Complex System - Requirement creep in Level 5

Level 5 (Complex System)	**Initial Requirement 145**		**Changed Requirement 135**	
	Cost	Time	Cost	Time
System	31.62	22.8	489.375	319.95
Co-ordination	8.75	6.75	139.50	105.75
Total	**40.37**	**29.55**	**628.875**	**425.7**

Table 16. Complex System - Requirement creep in Level 6

Level 6 (Complex System)	**Initial Requirement 80**		**Changed Requirement 70**	
	Cost	Time	Cost	Time
System	31.62	22.8	239.50	156.40

Table 16 Continued.

Co-ordination	8.75	6.75	66	52
Total	**40.37**	**29.55**	**305.5**	**208.4**

Table 17.Complex System- Requirement creep in Level 7

Level 7 (Complex System)	**Initial Requirement 60**		**Changed Requirement 40**	
	Cost	Time	Cost	Time
System	31.62	22.8	189.75	136.80
Co-ordination	8.75	6.75	52.5	40.5
Total	**40.37**	**29.55**	**242.25**	**177.3**

From the above Figures and Tables, it is understood that when the system which is in the complex region of the Cynefin framework, the decision maker needs to probe for solution. In terms of designing the system, the DM may use optimization to probe for the solution. In this case of LSCES, the decision makers need to use VDD along with MDO to find the solution due to the presence of coupling. When the requirement is changed in level 1 of the system, the breakdown of the system is already known to the DM and knows where the solution lies but the solution is unknown, he would have to gain experts advice to come up with a solution. So, the system falls under the complicated region rather than the complex regime of the Cynefin framework. In Exhibit 8, the state of the system determines the position of the system and this aide in understanding the decisions needed to be taken at different levels.

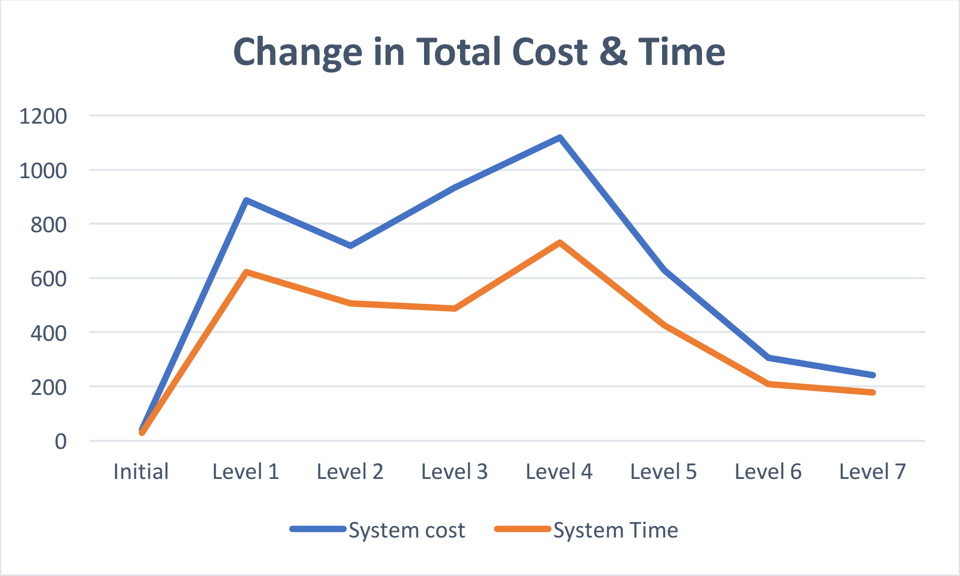

Figure 21. Change in cost and time with respect to requirement creep in Complex System

A graph is plotted as shown in Figure 21 for the total cost and time of the system when requirement creep occurs. From the graph, it is implied that the cost and the time of the system increases with respect to the coupling. In this case, there are couplings in 2,3,4 and 6th level and hence the cost with respect to those levels are relatively high when compared to level 7. The cost and the time of the system for level 1 is high due to the presence of being in the chaotic state for a long time.

From the above Figures and Tables in this chapter, the change in requirement produces a change in the cost and time due to presence of creep. The Cynefin framework is used to understand the state of the system which aids decision maker to understand where exactly the system lies in the framework. By understanding the state of the system, the decision maker can take different approaches to solve the creep within the organization. For instance, when the requirement of the Simple System is changed, the system which is in the Obvious region of the Cynefin framework is changed to Chaotic region. The decision maker practices the Best practices in the Obvious domain and when the state of the system is at Chaotic region, the decision maker needs to use

Novel practices to find the solution to make the system move to a different domain. The decision makers when in Complicated domain are required to use Good practices to move the system to the Obvious region of the Cynefin framework and use best practices. The optimal situation for s system is when the system is the Obvious domain and when the decision makers use Best practices for the system. In case of the Complex system, when the system moves to the complex domain during the requirement creep as shown in the Figure 20, the decision makers need to use Emergent practices to find the solution to move the system to the Complicated or Obvious domain of the Cynefin framework.

From these solutions, the decision maker understands the different situation the system endures and different types of practices he should practice for the system to be in the original state or the Obvious state. These solutions can help the decision makers within the organization to decipher the different situations the organization should deal with. These solutions in turn can also help the design teams to the understand the state of the system and the different tools that can be used at that state for designing. In this Chapter, organizational preferences were not considered while the state of the system were found for different systems. Every organization has different preferences and uncertainty associated within the organization with respect to the requirement and other preferences. The organizational preferences with respect to the uncertainty in the requirements are addressed in the next chapter of the thesis to understand the change in state of the system differs due to the different organizational preferences.

CHAPTER 6

EFFECTS OF UNCERTAINTY IN REQUIREMENTS ON CYNEFIN FRAMEWORK

The design and development of LSCES involves a number uncertainty in all aspects such as the design variables, requirements, attributes, manufacturing or other entities. In this chapter, sensemaking is used to address the uncertainty in the requirements and map it to the Cynefin framework. But it is noticed that, the organizational preferences are not taken in to consideration while using the sensemaking framework. Depending on the size, products produced, structure of the organization, market, ethics, employees and various other factors of the organization, the organization preferences are built[88]. Generally, for a top down approach, the preferences of the organization are determined by the upper management. The preferences of an organization help decision makers in deciding the different consequences that they must take at an event of creep in the scope during the design and development of LSCES. During the initial stages of design and development of LSCES the organization decides the budget, the cost overrun, timeframe of the project and other distinct factors that are applicable for the organization. Every organization has its own organizational preference and has corresponding risk preference associated with it [92].

From the previous chapter, it is understood that sensemaking framework can be used when a requirement creep occurs to understand the state of the system. The state of the systems helps the decision makers to understand what actions they can take when requirement creep occurs depending on the organizational structure and the complexity in the physics of the system. The requirement creep was induced in the system by changing the requirement at one level and keeping the other requirements constant. In this chapter, the uncertainty with respect to requirements is addressed, by varying the requirements at every level and relating it to the organizational preference. This work will address the Research Question 2 of the thesis and will provide the decision maker with a wide range of possible outcomes for different requirement creep and difference in the change of state of system. To understand the uncertainty, the requirement is changed one level by simultaneously varying the requirements at all the other levels varying.

The two systems - a simple system and a complex system which were used in the previous chapter are used to illustrate the effect of uncertainty on the state of the system. The requirements are changed to find the corresponding change in cost and time which will be used by the decision maker to understand the effects on the system and the state of the system. The movement of the system from one domain to other domains of the Cynefin framework is captured by the Cynefin dynamics. Different case studies with varying requirements creep are used in this chapter to establish the change in the state of the system.

The organizational preference for the hierarchical organizational structure used in this thesis is to 1) Stay within the requirement, 2) Reduce the cost and 3) At the event of a cost overrun, the cost overruns can be only up to 50% of the original cost decided. If the cost overrun for the system or project is beyond 50%, the organization can either scrap the project and start a new one or if the organization is large enough to absorb the costs, it can rebuild the project. In this thesis, the organization is assumed to be able to absorb the costs up to 150% overruns. The following Table 18 shows the allotted costs and time of development of the system.

Table 18. Organizational Preference due to Cost Overrun

System Type	Initial Cost	Initial Time	Acceptable Cost overrun	Acceptable Increase in Time
Simple System	60	50	90	75
Complex System	100	75	150	100

The requirements of the simple system and complex system for all the levels are provided in the Table 2 and Table 3. The uncertainty in requirements for a simple system and for the complex system are varied as shown in the Table 19. These levels are varied, to find the change in cost and time. It is then mapped on to the Cynefin Framework for the decision makers to understand and take better decisions.

Table 19. Uncertainty in Values of Requirement

Level	Simple System		Complex System	
	Initial Requirement Value	Requirement Range	Initial Requirement Value	Requirement Range
Level 1	1120	1150-1050	180	225-125
Level 2	1050	1100 – 1000	170	200-100
Level 3	1025	1045 – 945	160	175-75
Level 4	1000	1050 – 950	150	160-60
Level 5	975	975 - 875	145	145-45
Level 6	900	900 - 800	80	100-10
Level 7	150	150 - 50	60	60-10

Different series of trials runs are performed with the changes in requirements at different levels and different results are obtained. These results obtained are discussed for different cases.

Case 1: Increase in Requirements

The requirements of the levels are increased from the from the initial requirement to a higher value. At the event of increase in requirements, the system normally satisfies it by lying within the requirement. This indicates that the system will not be requiring any change, thereby not requiring any communication between the different levels of the organization. Hence, the state of the system remains in the Obvious domain and does not change when the requirements increase. It is the same in the case for both simple and complex system as there is no increase in the initial costs and time of the system. The initial cost and time when the system development occurs is provided in the Table 20 below.

Table 20. Actual Initial Costs of the Organization

Type	**Cost**	**Time**
System	32.63	23
Co-ordination	8.75	6.75
Total	**41.38**	**29.75**

The change in state of the system when the requirement increases is shown in the Figure 22 of the thesis.

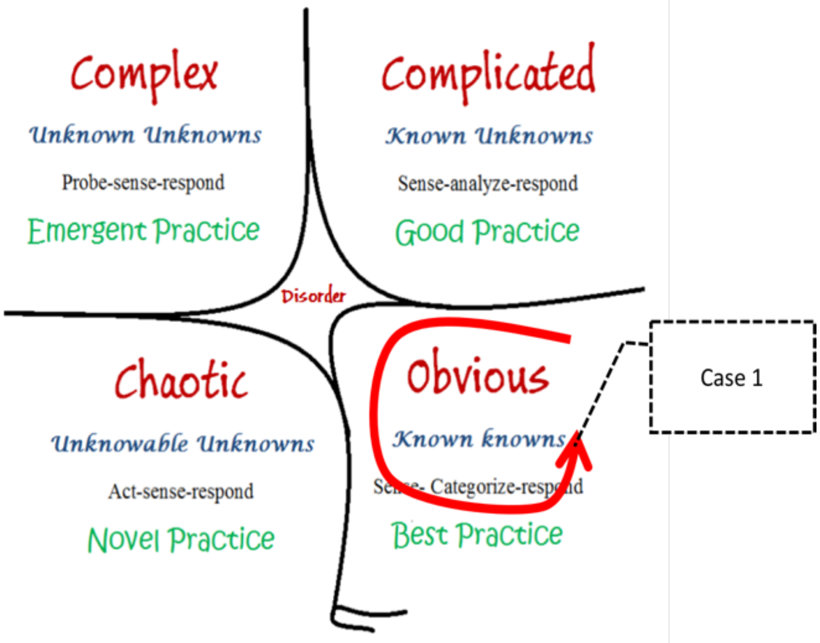

Figure 22. Case 1 - State of the system

Case 2: Decrease in Requirements for Simple System

First, the requirements of the simple system are reduced as it is very challenging to meet the requirement when it is reduced from the initial requirement value in all the levels of the system. The state of the system varies with the change in cost and time of the system which is required for the system to satisfy the requirement. The graphs of the simple for change in cost and time with respect to the requirement creep at different levels are provided in the Appendix C of thesis. The requirement of level 1 of the simple system is changed from 1120 to 1110, the change in cost of the system and the time of the system to satisfy the requirement is provided in the Table 21 below.

Table 21. Simple System - Requirement creep in Level 7

Level 1 (Simple System)	**Initial Requirement 1120**		**Changed Requirement 1110**	
	Cost	Time	Cost	Time
System	32.63	23	1068.8	720
Co-ordination	8.75	6.75	217.50	292.50

It is seen that the cost changes from 41.38 to 1286.3 and the time of the system changes from 29.75 to 1012.5. From the Figure 14 from the previous chapter, it is seen that the state of the system moves from Obvious → Chaotic → Obvious. From the Table, it is observed that the change in cost and time of the system is beyond 50% of cost overrun and is beyond the acceptable recovery time of the system. As the cost and time is very high, the organization does not try to recover the system and the state of the system is in Chaotic domain instead of moving to Obvious domain and this movement is shown in the Figure 23 of the thesis.

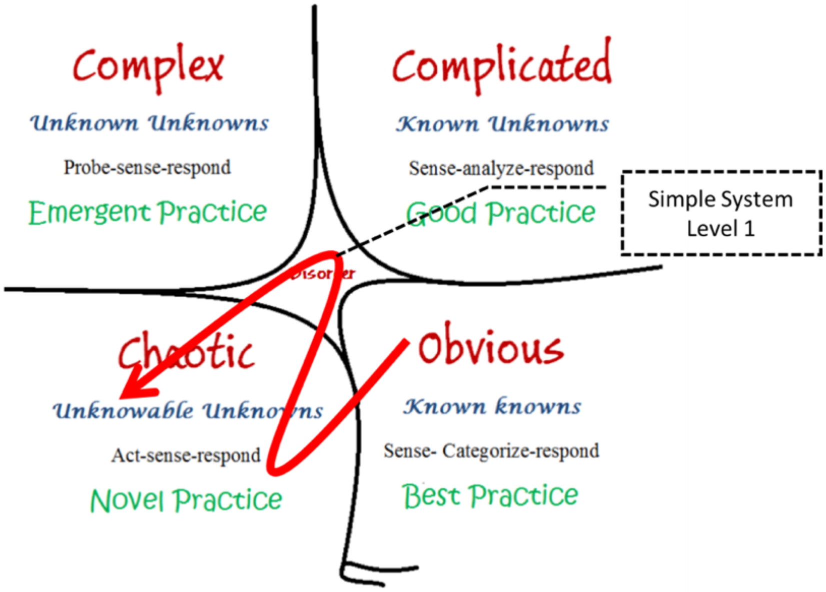

Figure 23: Case 2 - Change in State of the System for Level 1 in Simple System

For levels 2,3,4,5,6 and 7, at the event of requirement creep when the cost overrun is beyond 50%, the system moves to the Chaotic domain as it is not satisfied with the organizational preference. But in case of level 3 and level 4 of the simple system, the system behaves differently from the other levels of the simple system. For level 3 when the requirement is reduced to 985, the system crashes as there is no way to find a solution to comply with the requirement provided. From Figure 16 it is seen that for change in requirement at level 3 and level 4, the state of the system changes from Obvious → Chaotic → Complicated → Obvious. In this case when the system crashes, the state of the system changes from Obvious→Chaotic→ Complicated→ Chaotic. The same type of movement is observed for level 4 when the requirement of the system reduces below 950. This change in the state of the system which goes in to the chaotic domain for levels 3 and 4 is provided in the Figure 24 of the paper.

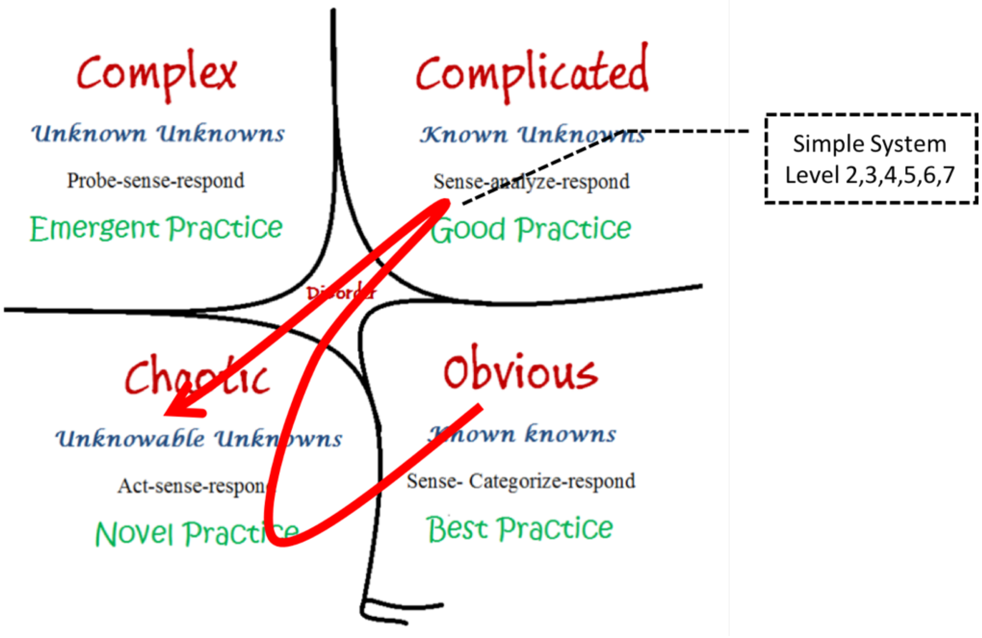

Figure 24.Case 2 - Change in State of the System for Level 2,3, 4, 5, 6 & 7 in Simple System

Case 3: Requirement Reduction in Complex System

Next, the requirements are changed in the complex system. The complex system is subjected to change in the requirements and the cost and time based on the requirements creep is used in this case study. Based on the change in requirements, when the requirement creep occurs the state of the system changes from Obvious→ Chaotic→ Disorder → Complicated → Obvious for level 1 and for other levels the state of the system moves from Obvious→ Chaotic→ Disorder → Complex → Complicated → Obvious and this is provided in the Figure 21 of the thesis. The change in cost and time to satisfy the requirement creep for the complex system is provided in the Appendix D of this thesis.

When the cost and the time to satisfy the requirement creep beyond the organizational preference, the organization scraps the system. Due to this, system moves to the Chaotic domain because of the Cynefin framework and retains there as the system is failed. The movement of the system for level 1 is from Obvious→ Chaotic→Disorder → Complicated → Chaotic and for other levels of the system is Obvious→ Chaotic→ Disorder → Complex→ Chaotic This change in the state of the system for a complex system for level 1 and other levels is provided in Figure 25 and Figure 26 of the paper.

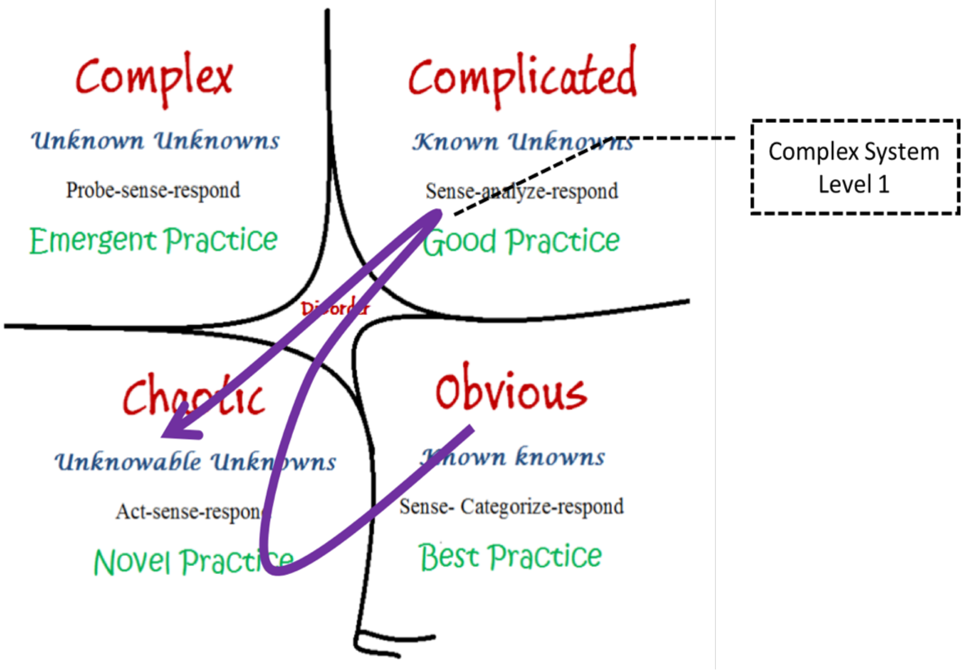

Figure 25. Case 3 - Change in State of the System for Level 1 in Complex

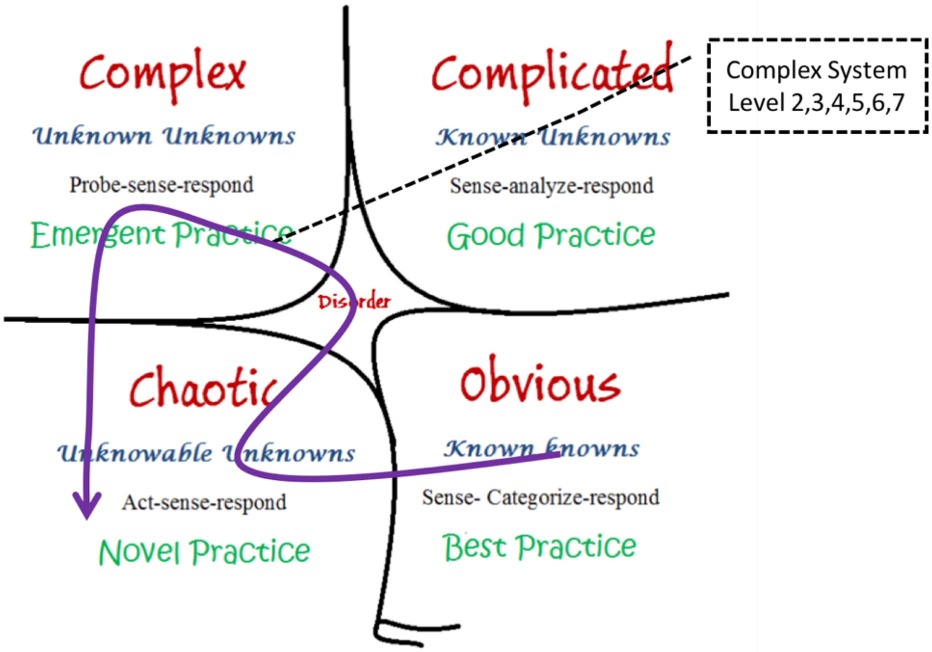

Figure 26. Case 3 - Change in State of the System for Level 2,3,4,5,6 & 7 in Complex System

Case 4: Special Cases

In special conditions, when the organization should continue with the development of the system, the organization needs to understand the amount of cost overrun it can absorb. In this case, for special conditions the organization is designed to absorbs cost overrun up to 150%. This is explained by an example. In level 5 of the simple system, when the requirement is changed from 975 to 945, the change in cost and time of the system is provided in the Table 22 below.

Table 22. Requirement in Level 5 of a Simple System

Level 5 (Simple System)	**Initial Requirement 975**		**Changed Requirement 945**	
	Cost	Time	Cost	Time
System	32.63	23	82.75	55
Co-ordination	8.75	6.75	19.25	23.5
Total	**41.38**	**29.75**	**112.50**	**78.5**

The cost overrun is beyond the acceptable but the organization needs to complete the project. Since, the cost overrun is 87.5% and it is below the percentage of cost which the organization can absorb, the development of the system is not terminated. The initial movement of the system is Obvious→ Chaotic→ Disorder → Complicated → Obvious as shown in Figure 29 of the thesis. The system movement changes to Complex domain from complicated as the organization must probe through different methods to solve this system within the constrained design space. The decision makers need to consider many attributes in this case to find the solution for the system. This movement of the system from Obvious→ Chaotic→ Disorder → Complicated → Complex → Complicated → Obvious is provided in the Figure 27 below.

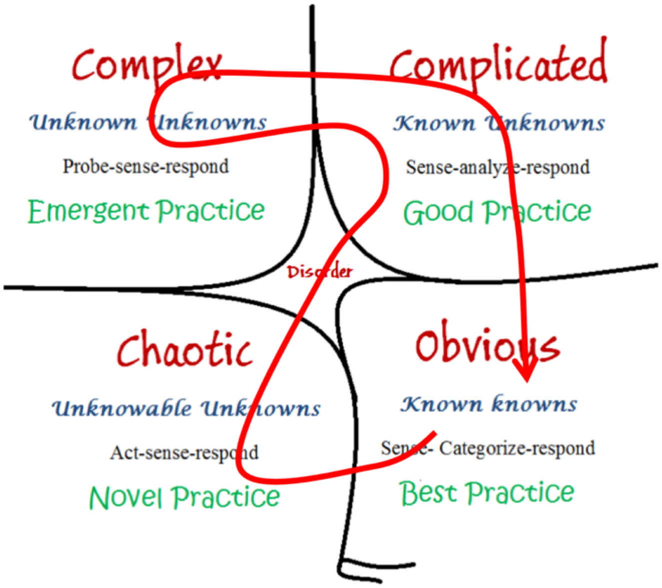

Figure 27. Case 4 - Movement of the Simple System

For the complex system, the organization can have different preferences when compared to the simple system. But when the similar situation occurs the system remains in the Chaotic region for a long time and then moves to the disorder region to find the next step in the process. The movement of the state of the system with respect to the complex system is shown in the Figure 28.

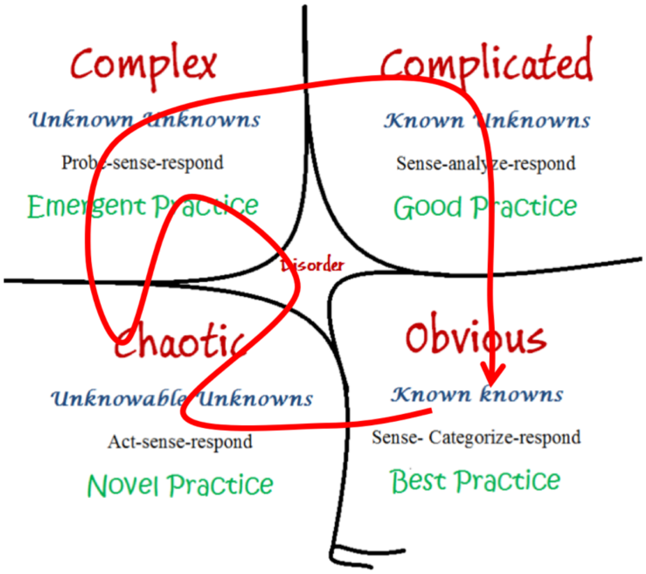

Figure 28. Case 4 - Movement of the Complex System

For Complex system, the decision makers are required to take various innovation steps to find the solution during the development process. The decision makers will have to go above and beyond the design space to find the right solution. It also represents negotiation across the different levels of the organization to satisfy the new requirement.

From the above cases, it is found that with respect to the organizational preferences, the uncertainty in requirements changes the state of the system previously considered to be true. Four different cases represent the change in the state of the system. This change in state of the system makes the decision maker understand the need of taking different approaches to solve for solutions during the design and development of LSCES as shown in Chapter 5. In this Chapter, the organizational preferences changed the state of the system when compared to the previous Chapter. The organizational preferences can move the state of the system depending on the preference, for example in Case 4 the simple system moved from Complicated to Complex but in case of Case 1 in Chapter 5, the state of the simple system does not go into the Complex domain of the Cynefin framework. The Cynefin framework used in this case can help in the improvement of system by reducing the cost and time associated to satisfy the requirements creep. This is performed by eliminating the system which produces the cost overrun beyond the organizational preference. The design and development of the system can thus be improved by using the Cynefin framework before the use of many rigorous methods that are used to capture the preferences of the stakeholder. The use of the Cynefin framework in the design and development of a LSCES is illustrated in the next chapter.

CHAPTER 7

CYNEFIN FRAMEWORK IN THE DESIGN AND DEVELOPMENT OF LSCES

As stated by Mike Griffin, a system is said to be elegant if it achieves the four attributes, effectiveness, robustness, efficiency and minimize the number of unintended consequences. Effectiveness deals with intended system operation and the real-time operation of the system. Robustness deals with the performance of the system in the presence of small disturbances. Efficiency of the system is when it produces desired results with less expenditure on resources and minimize the number of unintended consequences deals with reducing the failures due to extra features not needed for the system[4], [5]. Hence a Systems Engineer (SE) intends the system to be elegant in nature and this needs to be achieved for a LSCES.

The systems approach of the design and development of any system follows a top down approach or a bottom up approach. In general, in any LSCES, the system is designed using the top-down approach where the managers in the top management decide the preferences and break it down to lower levels. The design and development of LSCES comprises of three phases Conceptual design, preliminary design and detailed design phase as shown in the Figure 29[1], [2], [11], [21], [56].

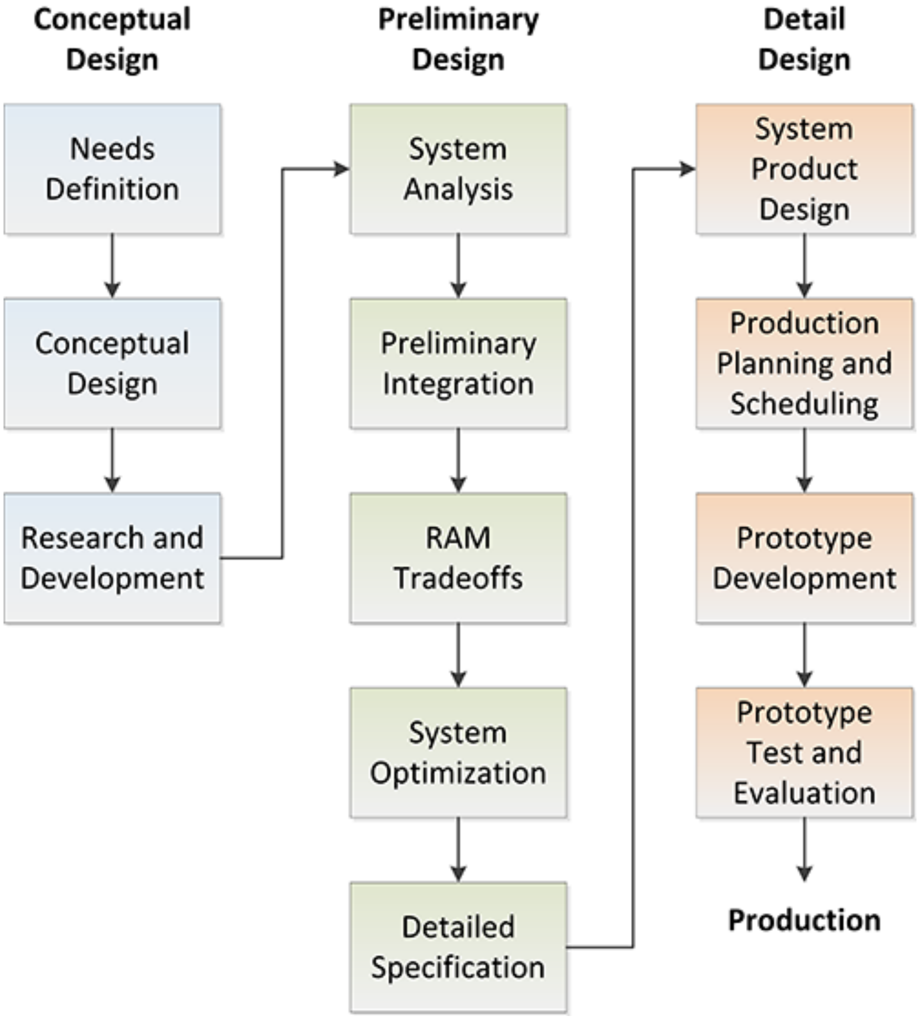

Figure 29. Design Phases in Systems Engineering [93]

The conceptual design phase is the early design phase in which the different concepts for the system are gathered and a design is emerged. They are usually in the form of sketches and models. The preliminary design phase consists of high-level design, which consists of details of the design such as schematics, layouts, diagrams. It is a region of ‘what’ and ‘how’s’ which are developed depending on the conceptual design phase. The detailed design phase is the final and elaborate design phase, which consists of all the details of the system. The system is usually modelled using solid modelling, drawings; different analyzes related to thermal, fluid, aero and financial modeling[6], [25], [94].

In this chapter, the different stages of design and development of LSCES are mapped on to the Cynefin framework and this Chapter discusses the Research Question 3 of the thesis. The framework is used to help the designer and DMs to freeze the various rigorous methods that can be used during the different stages of design and development. The different rigorous approaches discussed in the background are mapped on to the Cynefin framework. Rigorous methods are used to understand the changes in the Known and unknown structure so that people can understand the limitations of the system and what tools are needed to for decision making. These rigorous methods are used MDO, VDD and DA can be performed on the system's development at different regimes on the Cynefin framework. But before mapping the rigorous methods, the system should resolve all the ambiguity and understand the type of uncertainty pertaining in the system.

Uncertainty and Ambiguity

Uncertainty and ambiguity is prevalent at every stage of design and development of LSCES. Ambiguity and uncertainty can also be mapped on to the different domains of Cynefin framework from the Obvious region to the chaotic and in disorder depending on the information available using the Table of knowledge as shown in the Figure 9. In systems engineering ambiguity is occurs during requirements elicitation and due to lack of knowledge[1], [37], [45]. To resolve ambiguity, the ambiguity is mapped on the Cynefin framework. Ambiguity occurs at the state when there is no knowledge of the system and there are no solutions and so it leads to the system being in the Chaotic domain and the Disorder domain of the Cynefin framework. The other domains, such as the Obvious, Complicated and Complex do not ambiguity as there is information in the form of solutions in these domains. The ambiguity is mapped on to the Cynefin framework as shown in the Figure 30 of the thesis.

The Obvious, Complicated and Complex domain have uncertainty associated with them and they are unique to the respective domains depending on the information. Uncertainty which is present in the Obvious region is in the form of known distribution of solutions as the solutions is known and the Obvious domain is the domain of Known Knowns. The uncertainty in the complicated region is unknown probability distribution from which the solution needs to be found. The uncertainty in the complex region is depicted in the form of unknowable probability distribution where the solutions needs to be probed after finding the probability distribution. In the disorder and the chaotic region, there is no uncertainty as there is no way to find any solutions. The disorder and the chaotic region of the Cynefin framework deals with the ambiguity of the system. The other regions of the sensemaking do not have ambiguity as the decision maker or the designer would have enough information before being placed in the system. Ambiguity and Uncertainty are mapped on the Cynefin framework as shown in the Figure 30 below.

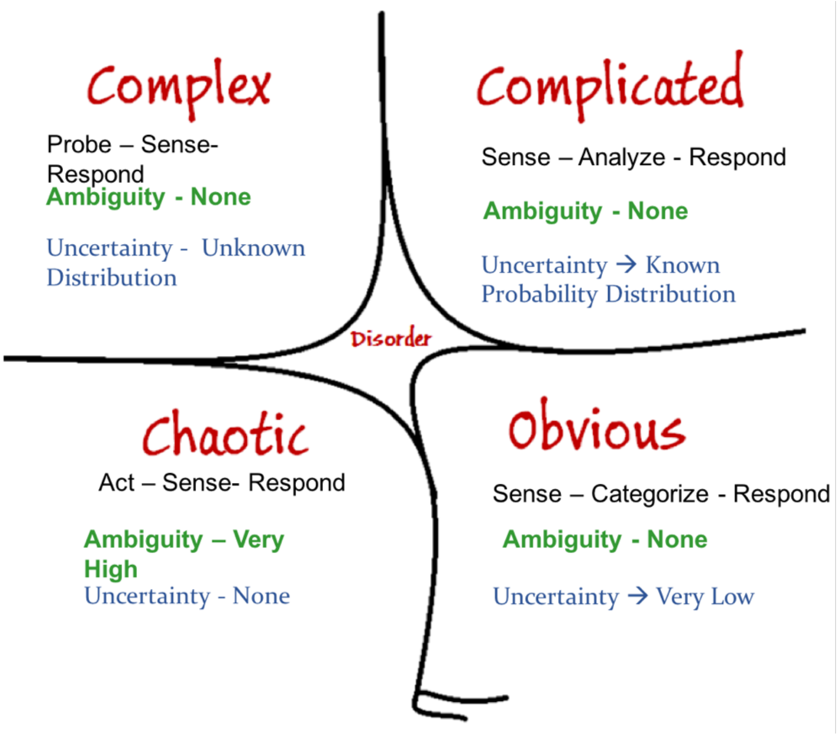

Figure 30 . Mapping of Ambiguity and Uncertainty on Cynefin Framework

DA, VDD and MDO

The rigorous methods such as the Decision Analysis (DA), Multidisciplinary Optimization (MDO) and Value-based systems engineering methods such as Value Driven Design (VDD) are mapped on to the Cynefin framework before mapping the different phases of design and development of LSCES. Decision Analysis is performed when the system is in the knowable and complex regimes. When the system is in chaotic regime, there is no possible way of executing the analysis as the entities of the system are not correlated[13]. VDD and MDO are one of the many rigorous methods that can be used in the presence of uncertainty. In the presence of ambiguity, the decision maker should make use of the sensemaking framework to understand the system, gain knowledge of different solutions and resolve ambiguity.

The Obvious domain is the domain of Known Knowns, where the solutions and the problem are known. For a simple system, the solutions are available without much of uncertainty and for complex systems, the results are available within the subsystem. Decision Analysis methods such as unilateral decision is used in the Obvious region for a simple system. And for Complex system, VDD and MDO use optimization techniques where the solutions can be found within the subsystem. This is mapped on to the Obvious domain of the Cynefin framework in Figure 31.

In Complicated region, there is presence of uncertainty as this is the region of Known Unknowns. In this domain, the solutions are available but they need to be analyzed for the problem available within the system. So, to find the solution, the decision maker can use decision analysis tools such as decision trees, influence diagrams for a simple system. For complex systems, MDO and VDD can be used by implementing optimization techniques to find the solution within the system for a complex system and for a simple system.

The Complex domain is the regions where the solutions are unknown and the problem is unknown too. In this domain, the decision maker can use multi objective decision making techniques such as the multi-attributes utility theory by incorporating the different attributes for the simple and complex systems. For large system, VDD and MDO can use optimization techniques with constrained design space to find the solutions.

Chaotic domain is the domain of Unknowable Unknowns, the decision maker cannot use decision analysis techniques as there is no information to find the solution. In this domain, the decision maker needs to take immediate action before analyzing the problem to save the system. But, this is also the domain to find new and novel solutions for the problem. This is the region of Novel practice. The decision makers must go beyond the design space to find the solutions. Hence for complex system, heuristic optimization techniques such as genetic algorithm can be used to explore the design space without constraints to find the starting point of the new system. Once the starting point is determined, it could be used to move the system to other domains depending on state of the system. The disorder domain is the region where the decision maker decides which region the system should be placed and so rigorous approaches cannot be used in this region.

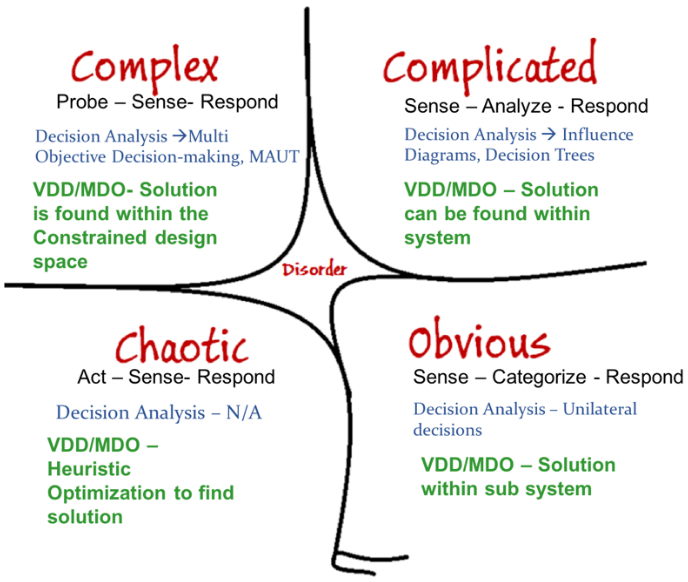

Figure 31. DA, VDD and MDO mapped on Cynefin Framework

Mapping for Design and Development Phases

Design and development of a LSCES follows the conceptual design, preliminary design and detailed design as shown in Figure 29. Now that the ambiguity, uncertainty and the rigorous approaches to find the value of the system are mapped on to the Cynefin framework, the design phases are mapped on to the Framework. The state of the system of the decision maker in this case it would be the designer.

Initially before the system is designed, the designer lies in the Disorder region of the Cynefin framework because the designer has less or no knowledge of the design and his state cannot be determined. During the Conceptual design phase the state of the designer moves from Disorder state to Complex state as designer knows that the design needs to emerge from the knowledge available. For this optimization techniques such as VDD and MDO can be used to probe the design space to find the optimal design with the given design variables and constraints. In the complex region, the designer deals with different uncertainties such as unknown probability distribution that can emerge after the application of VDD and MDO.

The Preliminary design phase, is the phase where the designers come up with more details of the conceptual plan. There are diagrams, schematics, layouts and the general framework of the system. The Preliminary design phase of the system has a set of entities which needs to be ordered. The designers have clearer picture of the system and so the system moves from the complex to the complicated regime. Different rigorous methods such as DA, MDO and VDD can be used to find the optimum solutions at the complicated region.

The Detailed design phase is where the design of the system is available in detail. All the information needed to design the system is available for the designer and hence all the uncertainties and the ambiguities are addressed. The detailed design has all the requirements and specifications in detail for the LSCES to be designed and hence the system moves from the complicated regime to the simple regime. This representation of the design phase is shown in the Figure 32.

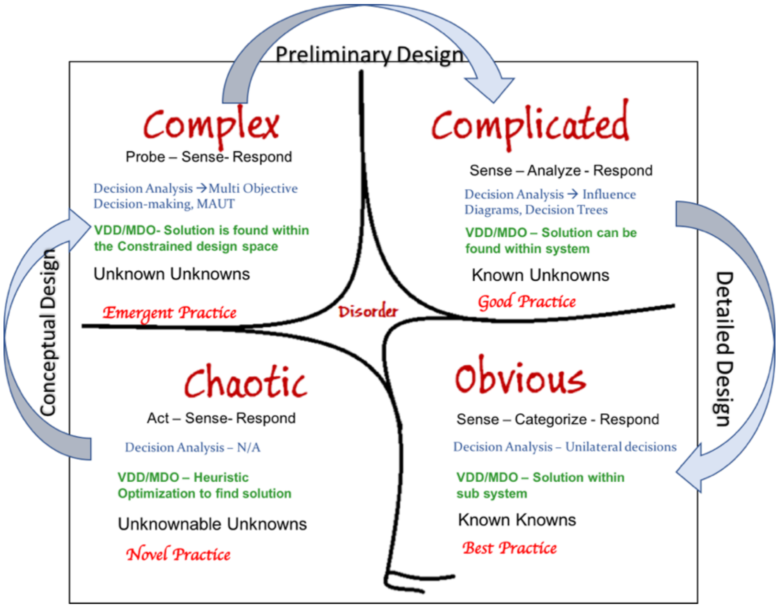

Figure 32. Design and Development phases on Cynefin Framework

From the above Figures, it is inferred the designers and the decision makers can use that Cynefin framework during the designing phase. It supports in the design and development of LSCES and in developing new systems by aiding the decision maker to resolve ambiguity and understand the uncertainty. This is then used to understand the different rigorous approached that can be mapped on to the Cynefin framework. These rigorous approaches aid the decision makers to use the different approaches to solve the problems during the different design and development phase as provided in the Figure 32.

The rigorous approaches mentioned in Figure 32 can now be also be used to identify the design phase of the system. If the system is in the obvious region, then it means that the system is in the detailed design phase. When there is change in requirement at the detailed phase of a complex system, the system moves to the chaotic region and then to complex which means that the system has to go through conceptual design phase to some extent and may have to re-conceptualize. This would involve change in alternatives and requirements at other levels of the organization. When the requirement of the simple system is changed, the system moves to complicated region where the system needs to go through expert's opinion which is nothing but the preliminary phase of the design. Here the decision maker needs to come up with decisions from different levels of the system to move the system back to the obvious region. Thus, the Figure 32 can be used to tie the different design phases during a change in requirement and vice versa.

CHAPTER 8

SUMMARY AND CONCLUSION

Summary and Conclusion

This research shows how the Cynefin framework, sensemaking framework can be used in an organization during the design and development of LSCES to understand the state of the system. Systems, be it simple, complex or complicated may fall under the chaotic region, where the decision maker should make quick decisions to restore the system back to running conditions. For instance, when the requirement is changed in the simple system as shown in the Case 1 of Chapter 5, the state of the system moves from Obvious region to the Chaotic domain as the decision maker needs to understand what caused the change in the system before resolving and moving the system back to the Obvious domain. The system goes to the Disorder domain in between the Chaotic domain and the Obvious domain for the decision maker to understand where the system would lie in the Cynefin framework. The state of the system changes for the different levels in the same system as shown in the Figures 14 and 15 for the simple system. For levels 2,3,4,5,6 and 7, the simple system moves from Chaotic domain to Complicated domain in the Cynefin framework so that the decision makers can use expert’s advice to find the solution to move back to the Obvious domain of the framework.

In case of the Complex systems, the state of the system changes from Obvious → Chaotic → Disorder → Complex → Complicated → Obvious as shown in the Figures 20 and 21 of the Thesis. The Decision maker at the different domains follow different set of actions to accomplish the decision-making process. Next, the organizational preferences of an organization, changes the state of the system as previously analyzed in Chapter 5. From Chapter 6, it can be inferred that in the presence of organizational preferences of an organization, the state of the system changes. The change is such that a Simple system can move to Complex domain of the Cynefin framework when the situation arises. These changes in the state of the system aids the decision makers to take appropriate actions in case of a requirement creep in accordance to the position in the Cynefin Framework. This helps in reducing the cost and time during the development of a system by either scraping the system when it does not meet the organizational preferences or rework on the system if it meets the criteria. The state of the system differs with the presence of uncertainty in requirements and this can be used by the decision makers to improve the decision-making process for a LSCES.

Now that the Cynefin framework along with its domains and dynamics is used to understand the state of the system and the process the decision maker can take at the domains, the decision maker can use it during the design and development of LSCES. For a system to be elegant, the system should be efficient, effective, robust and reduce the number of unintended consequences. For a LSCES, the systems engineers use the rigorous methods such as Decision Analysis(DA), Multidisciplinary Design Optimization (MDO) and Value Driven Design (VDD) to capture the preferences of the stakeholders. Ambiguity and uncertainty pertaining in the LSCES due to the preferences of the stakeholder should be understood before the use of rigorous tool such as DA, MDO and VDD. The Cynefin framework can also be used to understand the ambiguity and uncertainty during the design and development of the large-scale system. Cynefin framework is used to resolve the uncertainty and the ambiguity in the design and development of LSCES. The rigorous methods are mapped on the Cynefin framework to aid the decision makers use relevant methods to find the solutions. This research also shows how the different phases of the design of a LSCES such as the conceptual design phase, preliminary design phase and the detailed design phase move in the different domains of the LSCES and how the rigorous methods mapped on the Cynefin framework can be used by the decision makers to make better decision.

Future Work

Different fields were used for understanding and mapping the Cynefin framework, a sensemaking framework on to the design and development of LSCES and so there is potential for future work. In this thesis, a deterministic model was used to explain the process of sensemaking in traditional systems engineering process and in the design and development of LSCES. One type of organization structure was used to explain the process of sensemaking in LSCES. Future works can be made, to incorporate the different types of the organization structure, to find the effect of requirement creep on value and how the state of system is different when compared to hierarchical model. In this thesis, only one requirement was broken down to find the creep and change in the state of the system. Future work can be built on varying requirement creep in different requirements. Another phase of work can be to incorporate the Cynefin framework in an actual physics based system such as a commercial satellite system or a government based system. It can also be used to understand the differences in preferences with respect to the different types of organization involved.

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APPENDIX A

EQUATIONS OF SIMPLE SYSTEM

Organization Parameter	**Equations**	**Unit Cost**	**Unit Task Duration (Months)**
Spec. S1(V)	$A_{011} = X_{011}{*}X_{012}{*}X_{013} + A_{111}^2$	3.0	1.0
S11(A111)	$A_{111} = X_{111} + A_{211} + A_{221}$	2.0	1.50
S21(A211)	$A_{211} = X_{211} + A_{311} + A_{321}$	5.0	1.25
S22(A221)	$A_{221} = X_{221}^2 + X_{222}^2 + X_{223}^2 + A_{331}$	2.5	1.25
S31(A311)	$A_{311} = X_{311} + X_{312}^2 + A_{411} + A_{421}^2$	1.25	0.75
S32(A321)	$A_{321} = X_{321} + A_{431}^2$	1.25	0.75
S33(A331)	$A_{331} = X_{331}^2 + X_{332}^2 + A_{441} + A_{451}$	1.25	0.75
S41(A411)	$A_{411} = X_{411}^3 + X_{412}^3 + A_{511}{*}A_{512}$	1.5	1.50
S42(A421)	$A_{421} = X_{421}{*}24 + A_{531}$	1.5	1.25
S43(A431)	$A_{431} = X_{431} * 15$	1.5	1.25
S44(A441)	$A_{441} = X_{451}^2 + X_{452}^2 + A_{561} + A_{571}$	2.0	1.0
S45(A451)	$A_{451} = A_{581} + A_{591}$	1.0	0.75
S51(A511)	$A_{511} = X_{511}^2 + A_{611} + A_{621}$	1.0	0.50
S52(A521)	$A_{521} = X_{521} + A_{631}^2$	1.25	0.75
S53(A531)	$A_{531} = X_{531}{*}A_{641}$	0.75	0.75
S54(A541)	$A_{541} = X_{541}{*}X_{542} + A_{651} + 10\mathrm{A}_{661}$	1.25	0.25
S55(A551)	$A_{551} = X_{551}^2 + 5X_{552}$	0.50	0.50
S56(A561)	$A_{561} = X_{561} + A_{671} + A_{681}^2$	0.75	0.75
S61(A611)	$A_{611} = X_{611}^2 + X_{612}^2$	0.75	0.50
S62(A621)	$A_{621} = X_{621}^2 + X_{622}$	0.25	0.25
S63(A631)	$A_{631} = X_{631}{*}X_{622}$	0.25	0.75
S64(A641)	$A_{641} = \frac{X_{641}}{20}$	0.5	0.25
S65(A651)	$A_{651} = X_{651}^2$	0.125	1.25
S66(A661)	$A_{661} = 6X_{661}^3$	0.50	1.50
S67(A671)	$A_{671} = X_{671}^2 + X_{672}$	0.25	1.0
S68(A681)	$A_{681} = X_{681}^3 + 4X_{682}$	0.75	1.0

APPENDIX B

EQUATIONS OF COMPLEX SYSTEM

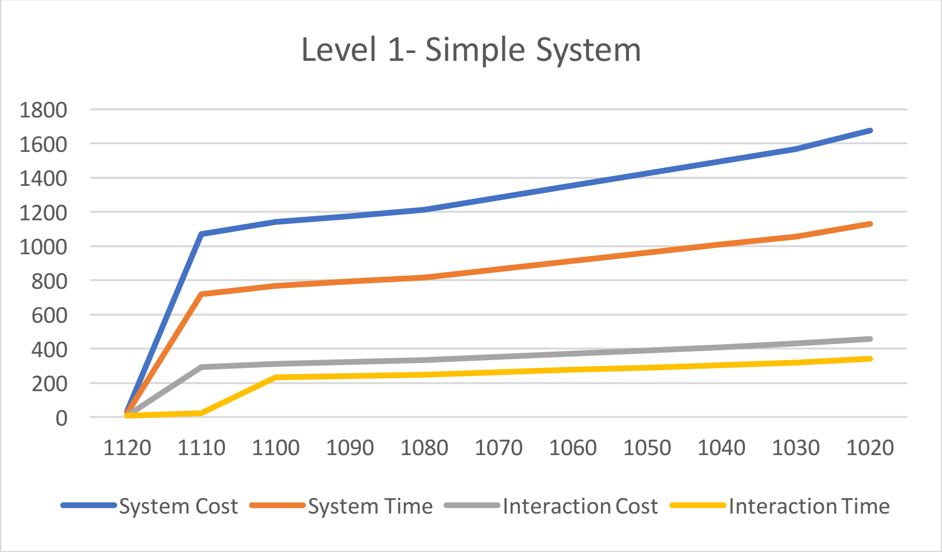
Organization Parameter	Equations	Unit Cost	Unit Task Duration (Months)
Spec. S1(V)	$A_{011} = A_{111} + X_{011} + \frac{A_{421}}{5}$	3.0	1.0
S11(A111)	$A_{111} = A_{211} + A_{221} + \frac{A_{541}}{5} + X_{111} * 5$	2.0	1.50
S21(A211)	$A_{211} = A_{311} + 2 * A_{321} + X_{211}$	5.0	1.25
S22(A221)	$A_{221} = A_{331} + X_{221}$	2.5	1.25
S31(A311)	$A_{311} = A_{411} + 2 * A_{421} + A_{671} * X_{311}$	1.25	0.75
S32(A321)	$A_{321} = A_{431} + X_{321} + \frac{\mathrm{A441}}{10}$	1.25	0.75
S33(A331)	$A_{331} = A_{441} + A_{451} + 2 * \mathrm{X}_{331}$	1.25	0.75
S41(A411)	$A_{411} = A_{511} + \frac{A_{541}}{20} + A_{521} + X_{411}$	1.5	1.50
S42(A421)	$A_{421} = A_{531} + X_{421}$	1.5	1.25
S43(A431)	$A_{431} = \mathrm{X}_{431} + X_{432} + A_{671}$	1.5	1.25
S44(A441)	$A_{441} = A_{541} + \frac{A_{311}}{3} * \frac{X_{441}}{10}$	2.0	1.0
S45(A451)	$A_{451} = A_{551} + 4 * 4A_{561} + X_{451}$	1.0	0.75
S51(A511)	$A_{511} = A_{621} + A_{611} + \frac{A_{671}}{5}$	1.0	0.50
S52(A521)	$A_{521} = A_{631} + 5 * X_{631}$	1.25	0.75
S53(A531)	$A_{531} = A_{641} + \frac{A_{331}}{10}$	0.75	0.75
S54(A541)	$A_{541} = A_{651} + A_{661} * 8 + X_{541}$	1.25	0.25
S55(A551)	$A_{551} = X_{551} + X_{552}$	0.50	0.50
S56(A561)	$A_{561} = A_{671} * A_{681} + \frac{A_{311}}{20}$	0.75	0.75
S61(A611)	$A_{611} = X_{611}^2$	0.75	0.50
S62(A621)	$A_{621} = X_{621} + X_{622}$	0.25	0.25
S63(A631)	$A_{631} = X_{631}^2 + X_{622}$	0.25	0.75
S64(A641)	$A_{641} = X_{641}^3$	0.5	0.25
S65(A651)	$A_{651} = X_{651} + X_{652}^2$	0.125	1.25
S66(A661)	$A_{661} = X_{661} + X_{662}$	0.50	1.50
S67(A671)	$A_{671} = \frac{X_{671}^2}{3} * X_{672}$	0.25	1.0
S68(A681)	$A_{681} = X_{681}^2 + 4X_{682}^2$	0.75	1.0

APPENDIX C

SIMPLE SYSTEM – COST AND TIME DUE TO REQUIREMENTS CREEP

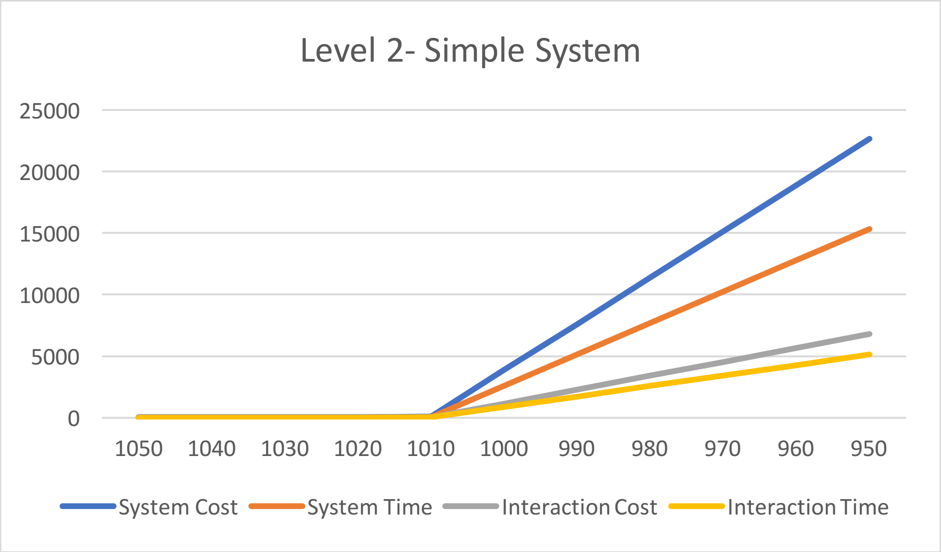
Simple System - Level 1

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
1120	32.6	23	8.75	6.75
1110	1068	720	292.5	21.75
1100	1140	768	312	232
1090	1175	792	321.75	239.25
1080	1211.3	816	331.5	246.5
1070	1282.5	864	351	261
1060	1353.8	912	370.5	275.5
1050	1425	960	390	290
1040	1496.3	1008	409.5	304.5
1030	1567.5	1056	429	319
1020	1674.4	1128	458.25	340.75



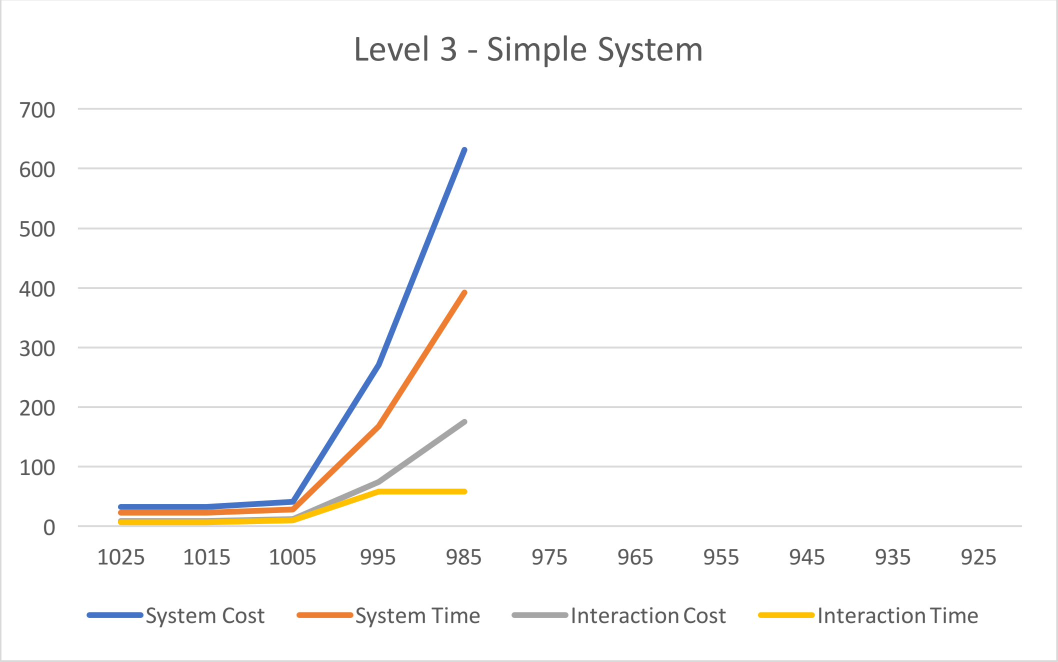
Simple System - Level 2

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
1050	35.625	23	8.75	6.75
1040	36.625	23	8.75	6.75
1030	32.625	23	8.75	6.75
1020	32.625	23	8.75	6.75
1010	75.25	51	22.5	17
1000	3887.8	2601	1147.5	867
990	7600.3	5151	2275.5	1717
980	11363	7701	3397.5	2567
970	15125	10251	4522.5	3417
960	18888	12801	5647.5	4267
950	22650	15351	6772.5	5117



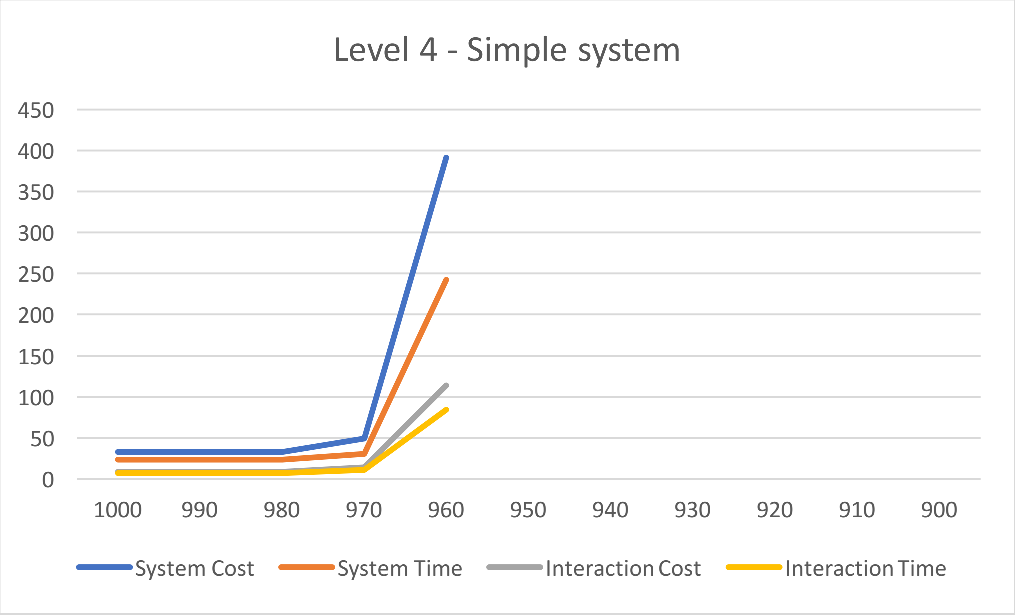
Simple System - Level 3

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
1025	32.625	23	8.75	6.75
1015	32.625	23	8.75	6.75
1005	41.125	28	12.5	9.75
995	270.75	168	75	58.5
985	631.75	392	175	58.5
975	No Convergence			
965				
955				
945				
935				
925				



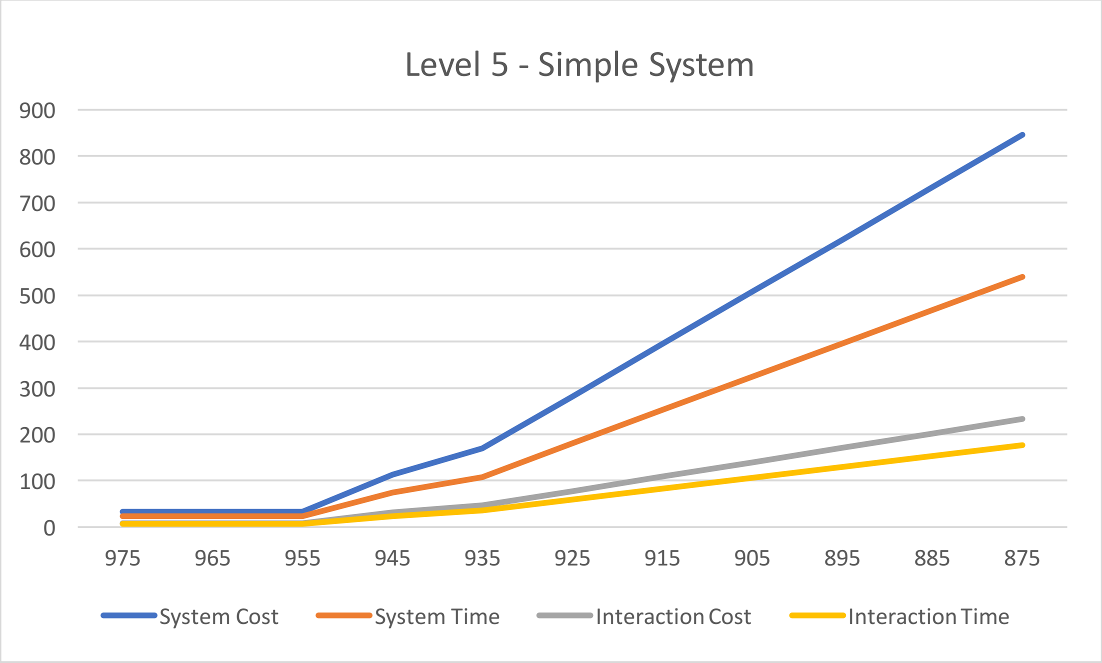
Simple System - Level 4

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
1000	32.625	23	8.75	6.75
990	32.625	23	8.75	6.75
980	32.625	23	8.75	6.75
970	48.875	30.25	14.25	10.5
960	391	242	114	84
950	No Convergence			
940				
930				
920				
910				
900				



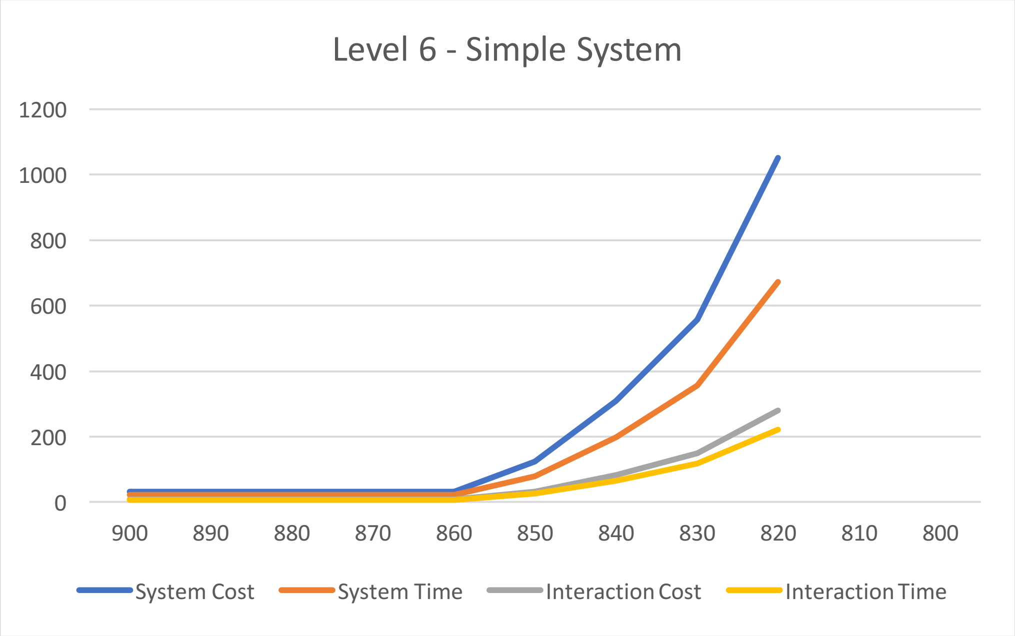
Simple System - Level 5

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
975	32.625	23	8.75	6.75
965	32.625	23	8.75	6.75
955	32.625	23	8.75	6.75
945	82.75	55	19.25	23.5
935	169.125	108	46.5	35.25
925	281.875	180	77.5	58.75
915	394.62	252	108.5	82.25
905	507.375	324	139.5	105.75
895	620.125	396	170.5	129.25
885	732.875	468	201.5	152.75
875	845.625	540	232.5	176.25



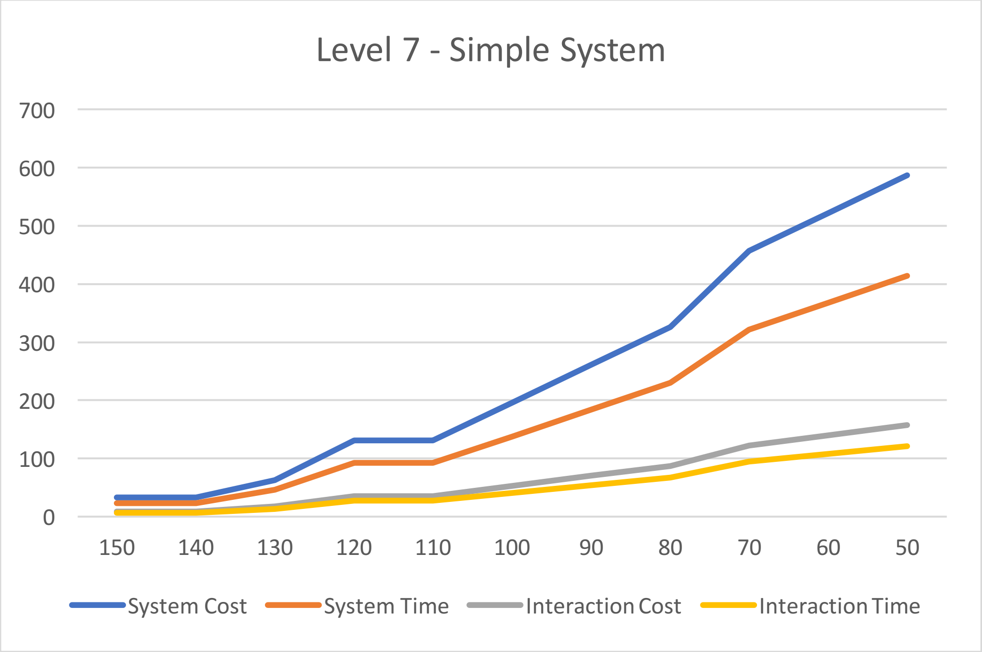
Simple System - Level 6

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
900	32.625	23	8.75	6.75
890	32.625	23	8.75	6.75
880	32.625	23	8.75	6.75
870	32.625	23	8.75	6.75
860	32.625	23	8.75	6.75
850	123.75	79	33	26
840	309.375	197.5	82.5	65
830	556.875	355.5	148.5	117
820	1051.9	671.5	280.5	221
810	No Convergence			
800				



Simple System - Level 7

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
150	32.625	23	8.75	6.75
140	32.625	23	8.75	6.75
130	62.25	46	17.5	13.5
120	130.5	92	35	27
110	130.5	92	35	27
100	195.75	138	52.5	40.5
90	261	184	70	54
80	326.25	230	87.5	67.5
70	456.75	322	122.5	94.5
60	522	368	140	108
50	587.25	414	157.5	121.5

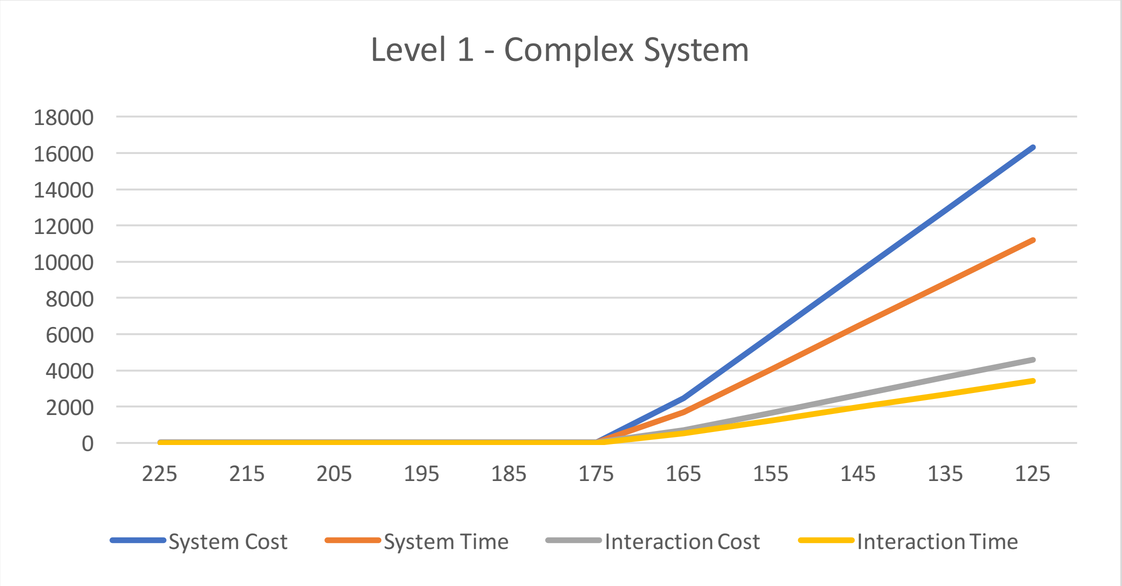


APPENDIX D

COMPLEX SYSTEM – COST AND TIME DUE TO REQUIREMENTS CREEP

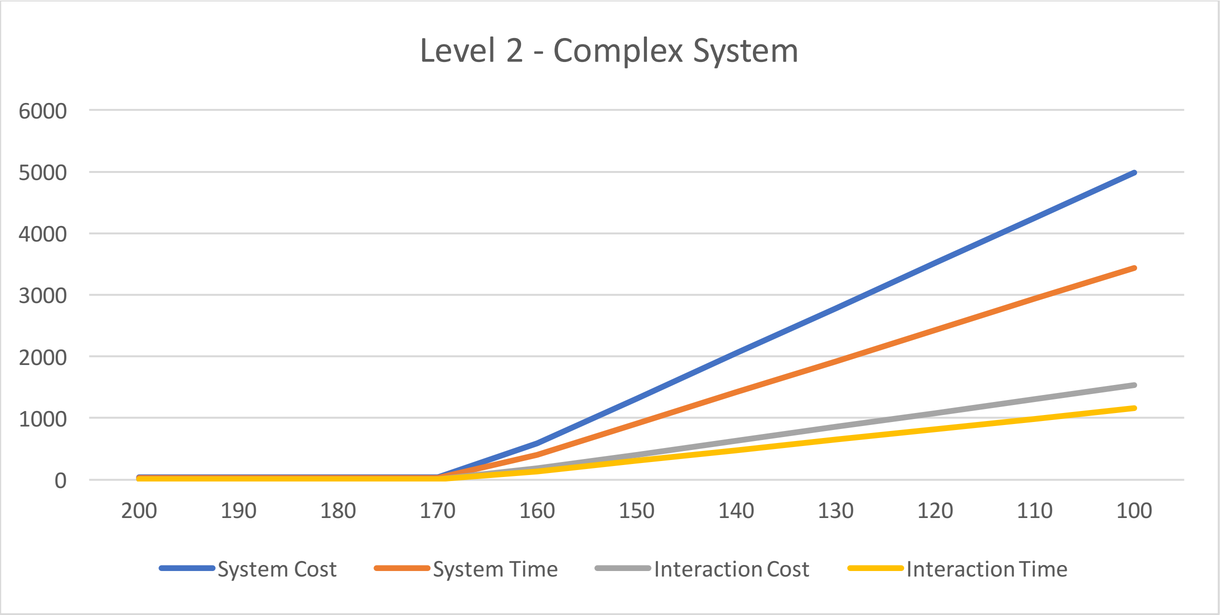
Complex System - Level 1

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
225	32.625	22.8	8.75	6.75
215	32.625	22.8	8.75	6.75
205	32.625	22.8	8.75	6.75
195	32.625	22.8	8.75	6.75
185	32.625	22.8	8.75	6.75
175	32.625	22.8	8.75	6.75
165	2458.4	1698.8	692.25	514.75
155	5920.9	4069.8	1667.3	1239.8
145	9383.4	6449.8	2642.3	1964.8
135	12846	8829.8	3617.3	2689.8
125	16308	11210	4592.3	3414.8



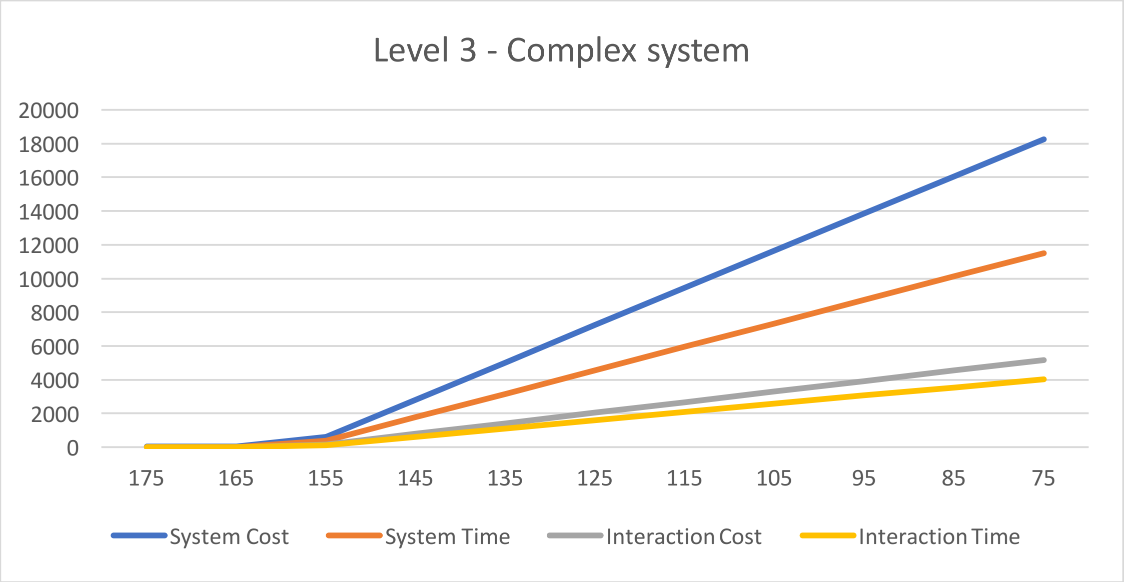
Complex System - Level 2

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
200	32.625	22.8	8.75	6.75
190	32.625	22.8	8.75	6.75
180	32.625	22.8	8.75	6.75
170	32.625	22.8	8.75	6.75
160	586	404.8	180	136
150	1318.5	910.8	405	306
140	2051	1416.8	630	476
130	2783.5	1922.8	855	646
120	3516	2428.8	1080	816
110	4248.5	2934.8	1305	986
100	4981	3440.8	1530	1156



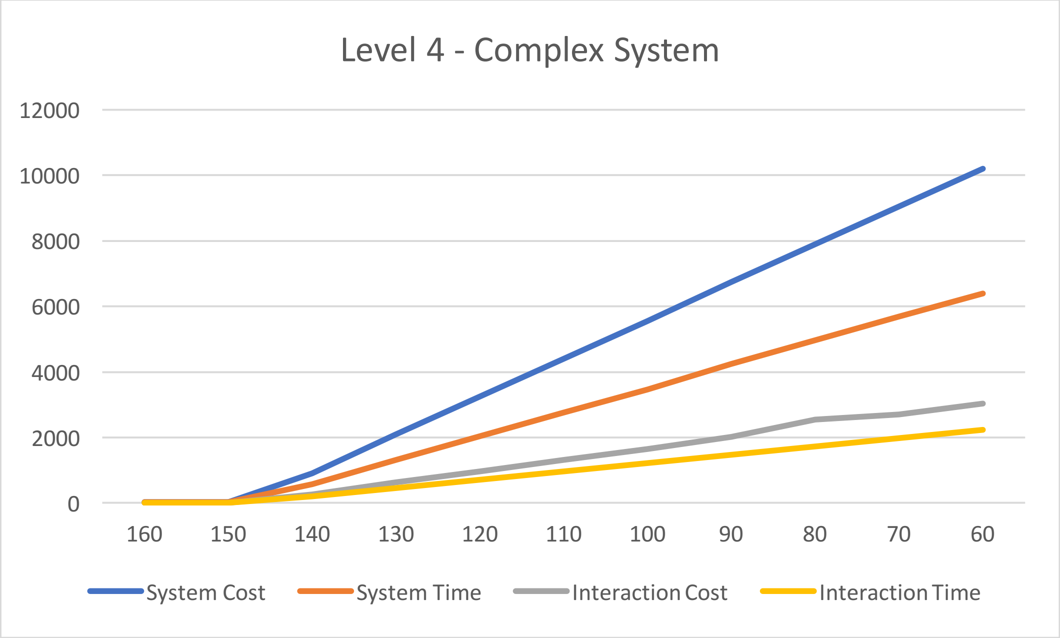
Complex System - Level 3

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
175	32.625	22.8	8.75	6.75
165	32.625	22.8	8.75	6.75
155	617.75	389.2	175	136.5
145	2824	1779.2	800	624
135	5030.3	3169.2	1425	1111.5
125	7236.5	4559.2	2050	1599
115	9442.8	5949.2	2675	2086.5
105	11649	7339.2	3300	2574
95	13855	8729.2	3925	3061.5
85	16062	10119	4550	3549
75	18268	11509	5175	4036.5



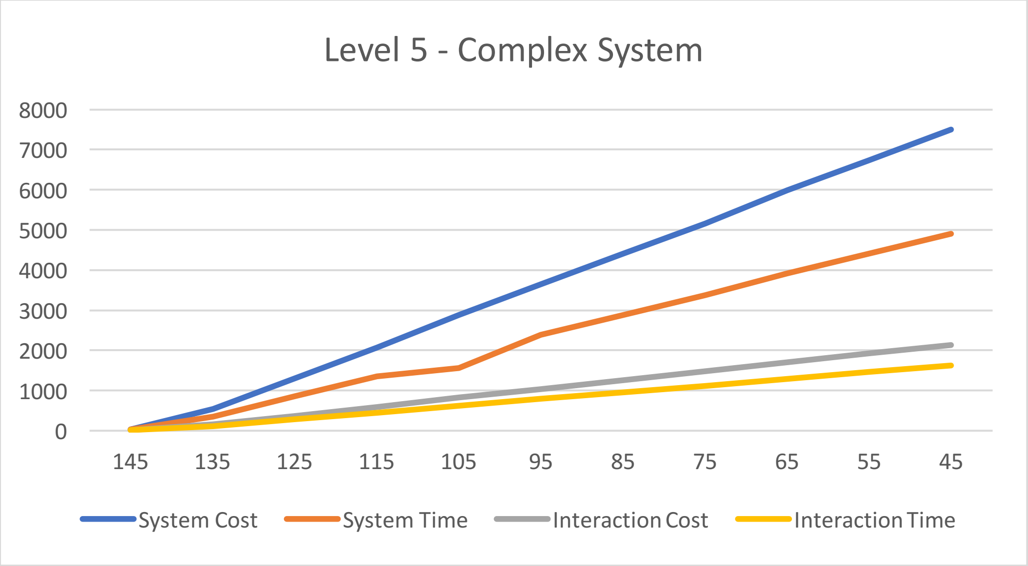
Complex System - Level 4

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
160	32.625	22.8	8.75	6.75
150	32.625	22.8	8.75	6.75
140	909.62	570.95	270.75	199.5
130	2106.5	1322.2	627	462
120	3255.5	2043.4	969	714
110	4404.5	2764.6	1311	969
100	5553.5	3455.8	1653	1218
90	6750.4	4237.1	2009.3	1480.5
80	7899.4	4958.3	2551.3	1732.5
70	9048.4	5679.4	2693.3	1984.5
60	10197	6400.7	3035.3	2236.5



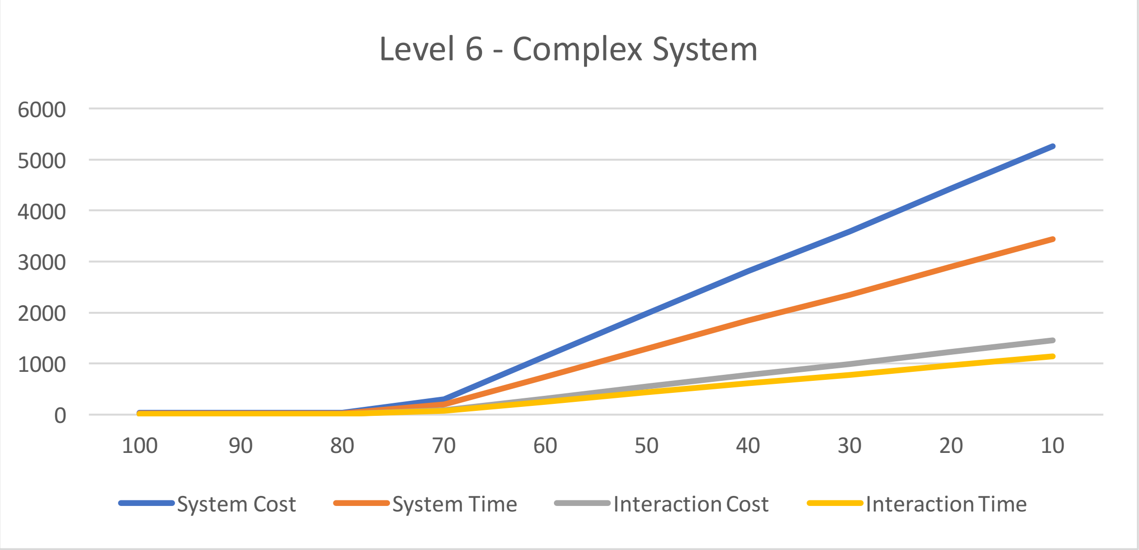
Complex System - Level 5

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
145	32.625	22.8	8.75	6.75
135	543.75	355.5	155	117.5
125	1305	853.2	372	282
115	2066.3	1350.9	589	446.5
105	2881.9	1554.1	821.5	622.75
95	3643.1	2381.8	1035.5	787.25
85	4404.4	2879.5	1255.5	951.75
75	5165.6	3377.2	1472.5	1116.3
65	5981.3	3910.5	1705	1292.5
55	6742.5	4408.2	1922	1457
45	7503.8	4905.9	2139	1621.5



Complex System- Level 6

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
100	32.625	22.8	8.75	6.75
90	32.625	22.8	8.75	6.75
80	32.625	22.8	8.75	6.75
70	299.37	195.5	82.5	65
60	1137.6	742.9	313.5	247
50	1975.9	1290.3	544.5	429
40	2814.1	1837.7	775.5	611
30	3592.5	2346	990	780
20	4430.8	2893.4	1221	962
10	5269	3440	1452	1144



Complex System -Level 7

Requirement	System Cost	System Time	Interaction Cost	Interaction Time
60	32.625	22.8	8.75	6.75
50	32.625	22.8	8.75	6.75
40	253	182.4	70	54
30	442.75	319.2	122.5	94.5
20	632.5	456	175	135
10	1135.5	820.5	315	243