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An Instrument to Assess Individual Capacity for System Thinking

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ABSTRACT

AN INSTRUMENT TO ASSESS INDIVIDUAL CAPACITY FOR SYSTEMS THINKING

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The purpose of this research was to develop and deploy a new systems thinking instrument to assess individual capacity for systems thinking using an inductive research design. While technology has been increasing exponentially, the corresponding methods to harness those technological advances, and the problems they have spawned, is lagging. While there is a broad collection of systems based methods, techniques, technologies, and tools that can be used in dealing with complex problems, these are predicated on an individual's capacity for engaging a level of systems thinking commensurate with their effective deployment. Research based methods to determine individual capacity for systems thinking were not found in the literature.

This research addressed the literature gap by developing an instrument to determine the individual capacity for systems thinking. To establish the characteristics for systems thinking, over 1000 systems based articles were analyzed and coded. Following grounded theory, as articulated by Strauss and Corbin (1990), a rigorous methodology was executed to inductively build the framework for systems thinking characteristics. Specialized software to support grounded theory, Nvivo (QRS International, version 10, 2014) was used to navigate and manage the large amount of qualitative and quantitative data for the research. A mixed method approach was used to collect and analyze qualitative and quantitative data in the initial instrument development.

After deriving the set of systems thinking characteristics, a non-domain specific systems thinking (Sc) instrument was constructed to capture and measure the state of systems thinking at the individual level. The instrument consists of 39 binary questions with fourteen scored scales to measure seven main systems skills preferences.

Following a pilot study for application of the instrument, it was administered to 242 participants. To establish validity, multiple validity checks including face validity, internal validity, conclusion validity and content validity were performed. Reliability testing was also conducted, including Cronbach's Alpha Test and Parallel Test, with excellent results.

The results of the research show significant promise for the instrument to capture the capacity of individuals to engage in systems thinking. The document concludes with directions for future research and implications for practitioners related to the capacity of individuals for systems thinking.

DEDICATION

This thesis is dedicated to:

My wife: Sawsan, who gave me strength, love, and motivation throughout the journey of my doctoral study while pursuing her own Ph.D.

My father: Mohammad, with his endless support and strong belief of me.

My dearest Mom: with her love, affection, prays, and patience to see me become a professor one day.

My sisters: Dr.Dima, Dr.Esr'a, Dr. Rawan, Dr. Raghad, Dr. Dana, Tala, and Hala for their gentle prodding and being there for me all the times.

My daughter: Kenda, you are, therefore I am.

And finally to the soul of my little brother.

Words are just not enough to express how grateful I am to have all of you on my side.

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CHAPTER I

INTRODUCTION

Dealing with complexity and its associated problems is a reality for engineering solutions to complex problems of the 21st century. There is a special class of systems, and their representative problems, of particular interest. This class, referred to as system of systems (SoS), has been receiving increased attention in the literature, including emergence of a journal, *International Journal of System of Systems Engineering*, which is devoted to the study of this field and associated phenomena. At a most basic level, SoS is concerned with the integration and coordination of multiple systems, considered a unity, that functions to achieve performance, purpose, or behavior that none of the individual constituent systems is capable of independently. The SoS problem domain is exacerbated by limitations of 'hard' technology based solutions developed without due considerations for the 'soft' non-technology aspects of holistically developed solutions. To better grapple with this emerging SoS domain, many organizations attempted to address system of systems related issues which have become the focus of many organizations (e.g. National Centers for System of Systems Engineering). Concepts of systems of systems have a multidisciplinary applicability, ranging from healthcare to defense.

Traditional approaches to engineering of systems (e.g. traditional systems engineering) has been challenged as suspect (Keating, et al. 2003; Checkland, 1993;Weinberg, 1975; Chen and Clotheir, 2003) for application to this new class of problems marked by high levels of ambiguity, uncertainty, and emergence. As mentioned above, the traditional science based approach (system engineering) for dealing with problems is to reduce (reductionism) the problems into parts and derive solutions as a function of the understanding of the parts. This approach is sufficient in systems where problems are well bounded and relationships can be understood in direct correlation to performance (outputs). However, this is not the case in large, complex, multidimensional problems.

Despite being successful for many years, traditional systems engineering (TSE) is not intended to address problems that are mired in: " i) turbulent environmental conditions; ii) ill-defined problem conditions; iii) contextual dominance; iv) uncertainty of appropriate approach; v) ambiguous or changing expectations and objectives; vi) unclear integration concerns for multiple complex systems; and, finally, vii) excessive complexity" [Keating, (2009), p. 177]. In sum, the ability of traditional reductionist based approaches to dealing with the emerging class of "system of systems" problems is in doubt. For engineers and managers who must operate on these problem domains, it also suggests that a different level of thinking is necessary.

This chapter provides an introduction to the nature of this research by explaining the significance and the purpose of the study. Following this, the research questions and hypotheses are presented with an explanation of the intent of each question. The last section of this chapter provides research definitions and limitations necessary to fully appreciate the research.

RESEARCH SIGNIFICANCE

System of systems is still an emerging field and currently there are insufficient tools and techniques purposefully designed for large socio-technical applications (Keating, 2009). With the exponential increase in technology and the emerging complex problem domain characteristic of modern society, engineers, managers, decision makers and other professionals are frequently faced with the challenge of making decisions at various levels of their systems. The complex problem domain is marked by **(1)** increasing complexity, **(2)** the exponential rise in information, **(3)** ambiguity, **(4)** emergence and **(5)** high levels of uncertainty. Dealing effectively with problems exhibiting these characteristics requires knowledge not only of technological issues but also of the inherent human/social, organizational/managerial, and political/policy dimensions that solutions to these issues must consider. In effect, a holistic perspective integral to systems thinking is necessary for professionals to effectively navigate this problem domain.

Currently, there are insufficient tools and techniques purposefully designed to deal with complex problems domains. At best, there are emerging methodologies and a selection of existing tools from related fields (e.g. stakeholder analysis, objective tree, lean sigma, etc.). Most of these tools and techniques focus more on the technical perspective of the problem domain. This is not a criticism of these techniques or the fields from which they are derived. On the contrary, this suggests that these techniques, while they might currently satisfy a need, have not been designed and specifically structured as techniques for facilitation of socio-technical problem solutions. Effective tool selection and utilization requires appreciation of the uniqueness of the problem domain, context, and the design of an appropriate methodology as well as matching the corresponding tool(s) to the specific application. Without a thorough appreciation of this unique confluence of context, problem domain, and methodology, the conditions are set for incompatibility or mismatch between problem, context, and appropriate approach/tools. The result is most often a failure to produce desirable or sustainable solutions or feasible actions in the complex problem domain. The ability to determine this mismatch is a function of higher order 'Systems Thinking'. Keating (2005) stipulates that in consideration of SoS applications "it is important to note that the determination of appropriateness is a function of the other levels [views], the context, and the system of system problem" (p.4). This certainly applies also to the selection of supporting tools for SoS efforts. Thus, there is a present concern, amplified in the evolving SoS literature, focused on the lack of adequate supporting tools to effectively engage SoS problems and the problem domain within which they are embedded. This does not suggest that SoSE cannot be performed or have satisfactory results. On the contrary, it suggests that SoS may be better served by specific purposefully constructed tools that have been built for SoS applications rather than those that have been modified from other fields.

Large complex problems are principally philosophically, axiomatically, and conceptually driven, suggesting the importance of a systemic worldview. Therefore, the capacity of individuals to engage in a level of systems thinking that permits a sufficiently robust worldview to be effective in the complex problem domain is essential. Thus, there is significant utility for tools capable of determining the individual's level of thinking (worldview) appropriate to engage the systems thinking essential to effectively deal with complex problems. After an extensive review of the complex systems/system of systems,

systems theory and systems engineering literature, it must be concluded that such a tool to determine the level of systems thinking for an individual does not currently exist. Therefore, the significant original research is suggested to:

develop and test an instrument to capture the state of systems thinking at the individual level that would indicate predisposition for effective engaging in the complex problem domain. This research derived instrument will generate an individual systems thinking profile.

This research is driven by three primary points of emphasis:

- There is a significant gap in the complex systems/SoS literature that can be filled by the development of an instrument to determine the level of systemic thinking for individuals who must deal with complex problems. The intent is to show that the current methods and instruments are insufficient for determining the capacity for systems thinking necessary to be successful in complex system problem domains.
- The proposed systems thinking instrument will capture the state of systemic thinking at the individual level. This offers a starting point to better understand individual capacity to engage complex multidimensional problems.
- The proposed instrument will examine the predisposition of engineers, managers, decision makers, and other professionals for systems thinking necessary for higher level functioning in dealing with complex multidimensional problems.

As the problems that individuals deal with evolve and become more complex, the need to establish new tools to enhance effectiveness becomes critical. The primary goal of this research is to advance the development of an appropriate method that can support individuals who must deal with complex problems domains. Table 1.1 below shows the contributions of this research across theoretical, methodological, and practice dimensions.

Table 1.1: Anticipated Contributions of the Research

Aspect	Contribution
Theoretical	• A framework for systems based complex systems attributes.
Methodological	• Systems thinking instrument to classify and represent the level of systemic thinking for individuals who deal with complex problems. • Creation of an instrument to support the larger application of the systems based methodologies (e.g. SoSE methodology). • Provide an instrument to develop a profile that assesses the level of systems thinking for an individual.
Practical	• Implications for training and applications for development of managers, engineers and professionals. • Match individual potential with job requirement by assessing the level of systems thinking for an individual. • Help engineers, business leaders, managers, and others to determine capacity to engage complex problem problems domains. • Provide better understanding of the different types of systems thinkers required for specific job classifications.

RESEARCH PURPOSE

In system of systems (SoS) there are a broad collection of methods, techniques, technologies, and tools (Keating, 2009) that can be used. The current development of the systems thinking instrument is focused on the necessity of developing designed and structured tools and techniques for facilitation of a complex problem domain. There is currently a lack of knowledge and development of purpose built and tested techniques supportive of this complex system problem domain. In particular, SoS relies heavily on fitting an appropriate team to the problem (Adams & Keating, 2011). Unfortunately, there is not currently a set of implementation tools specific to SoS to assist in this team design activity with respect to determination of the capacity of individuals to engage in the level of systems thinking necessary for successfully navigating the complex system problem domain.

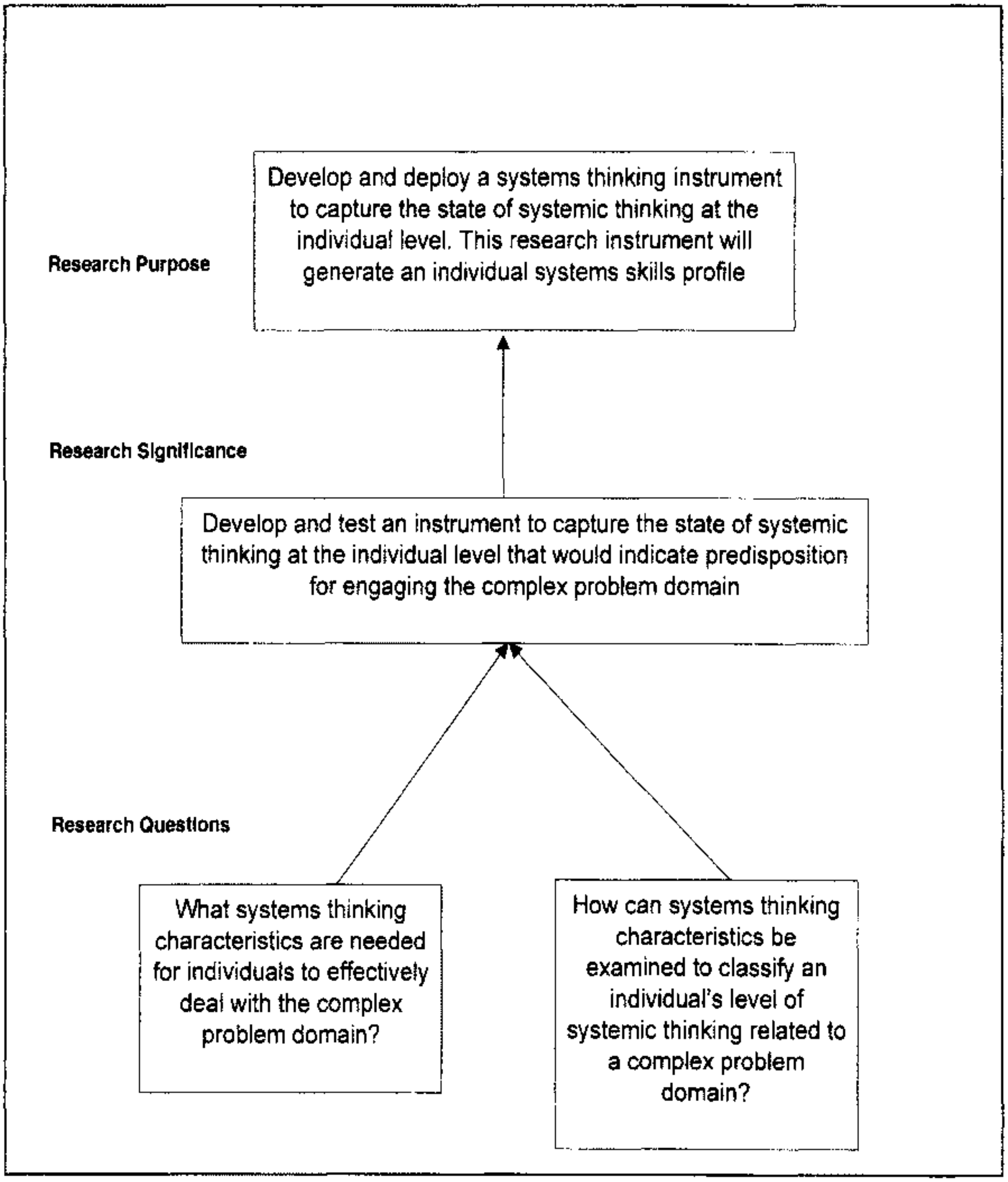
There are two broad assumptions that offer a challenge in maturing SoS research. First, SoS is sufficiently different from SE such that a direct extrapolation of SE tools to the SoS domain is questionable. Second, the nature of the socio-technical problem domain is such that systemic thinking of team members is critical and will impact the effectiveness of a systems based effort. Developing new approaches for understanding the level of systemic thinking among prospective team members, supported by corresponding methods and tools, is a significant challenge to further the development of the systems based approaches dependent upon the systems thinking capacity of individual participants.

This research is proposed in response to the new realities facing future engineers, managers, and decision makers who must deal with a complex problem domain. The research is targeted to further develop and apply a systems thinking instrument to assist with identification of individuals with capabilities to more successfully navigate the complex problem domain. This new survey instrument supports better understanding of the individual capacity to effectively deal with problems that are complex in nature and would benefit from systems thinking that is independent of specific domain knowledge, skills, or abilities. The anticipated outcome of this research will provide a profile that presents the systems thinking characteristics held by an individual. These are the very characteristics that are needed for individuals to effectively deal with these problems. The systems thinking instrument will help identify the level of systems thinking for individuals and their potential capacity to successfully engage complex system problems. In effect, the instrument will develop the degree to which their particular systems worldview is compatible with the complexity, uncertainty, ambiguity, and emergence inherent in the complex problems domains

The purpose of this research is to develop and deploy a systems thinking instrument to capture the state of systemic thinking at the individual level to deal with complex problem domains.

Figure 1.1 shows the overall structure of the inquiry. The research purpose was supported by the research significance and answered by the two primary questions in the next section.

Figure 1.1: Structure of the Inquiry



RESEARCH QUESTIONS

For this research there are two primary questions:

Question one: *What systems thinking characteristics are needed for individuals to effectively deal with the complex problem domain?*

It is imperative to mention that system theory and systems thinking are the key to understanding complex systems problems. The key to this research question is building these characteristics from the systems literature. The rigorous examination and response to this question will provide a set of characteristics which can provide an intellectual foundation to support development of an instrument in response to question two.

Question two: *How can systems thinking characteristics be examined to classify an individual's level of systemic thinking to deal with a complex problem domain?*

There is not currently an approach, method, or supporting tool, grounded in the system theory body of knowledge, to determine the state of systems thinking for an individual. The response to this question will determine the feasibility of constructing an instrument capable of determining the level of systems thinking that exists for an individual.

RESEARCH HYPOTHESES

The alternative hypothesis of this research is:

H_1: *There is a statistically significant relationship between the proposed Systems Thinking Characteristics (Sc) and the state of systems thinking at the individual level that would indicate predisposition for engaging in the complex problem domain.*

Which is tested against the null hypothesis:

H_0: *There is no statistically significant relationship between the proposed Systems Thinking Characteristics (Sc) and the state of systems thinking at the individual level that would indicate predisposition for engaging in the complex problem domain.*

In effect, the hypothesis to be tested attempts to test the relationship of the systems thinking characteristics (developed inductively from the system literature) to the level of systems thinking for an individual. In this first attempt to establish such a relationship, the research synthesizes the literature from systems and proceeds to test this against the level of systems thinking for an individual.

DEFINITIONS OF TERMS FOR RESEARCH

The following definitions and perspectives are provided to clarity the concepts that will be used throughout this study. Although some of the concepts have multiple definitions and interpretations, the following literature based perspectives will be used for this research.

- **Complex System Problems/ System of Systems (SoS)**

There are numerous definitions and perspectives of SoS. Multiple authors have elaborated on the meaning of SoS (Keating et al. 2003; De Laurentis et al. 2007;

Hitchins, 2003; Sage and Cuppan, 2001; Ring and Madni, 2005; Kaplan, 2005). Sousa-Poza et al. (2008) mentioned that this variety of perspectives, particularly early in the development of the SoS field, is healthy. However, as the field matures it is desirable, as the field stabilizes, to come to some level of consensus around accepted knowledge. For purposes of this research, the following definition for systems of systems will apply: "*Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development.*" [Sage and Cuppan, (2001), p. 326] While there are other definitions, this definition enjoys a significant following in the literature. With respect to complex system problem domain, the following characterization, consistent with earlier works of (Keating and Katina, 2011; Katina et al. 2014) and the notion of Ackoff's (1997) 'messes' and Rittel and Webber's (1973) 'wicked problems' provides the following table:

Table 1.2: Complex System Problem Domain Perspective (Keating, et al. 2014)

Characteristic	Perspective
Proliferation of information	The information explosion has created unparalleled levels of quantity as well as access to information, creating an overabundance of information that individuals must accommodate.
Conflicting perspectives and divergence in stakeholder views	Given the abundance of information and varying degrees of interpretation, conflicts in perspectives concerning situations, and the appropriate path forward for their resolution, are inevitable. This requires that individuals be capable of dealing with multiple, potentially conflicting, worldviews.
Scarce and dynamically shifting resources	Resources have always been scarce and constrained. However, the short view and demands for immediate response to emergent issues creates a climate of instability in assurance of continuing resource availability. This requires that individuals be capable of dealing with high levels of uncertainty in resources as well as emergence in a situation.
Unintended consequences	High degrees of uncertainty and incomplete knowledge exacerbate the occurrence of behaviors that were not intended. Therefore, individuals operating in this domain must deal with emergent conditions.

Table 1.2: Continued

Ambiguous boundaries	Boundaries are essential to determine what is included and excluded in a complex system. They can be arbitrary, permeable, and dynamically shifting. Dealing with ambiguity, and particularly ambiguity in boundaries, is essential for individuals to operation in this domain.
Politically charged positions	Politically charged environments for complex systems are marked by attempts to pursue strategies to influence decisions, actions, and interpretations. This implies that individuals operating in this problem domain appreciate and adapt to the inevitable political dimensions of the domain.
Solution urgency	There has always been an urgency to resolve issues related to complex system problems. However, current environments are increasing the demands for instant gratification and resolution of system problems. As such, individuals not only must deal with the inevitable time dimension, but also the creation of responses that are 'satisficing' to the situation.
Unclear entry point or approach	The degree of complexity for modern systems and their resulting problems occur on a continuous basis. There is no prescription or clear point of entry or exit to address the issues. This requires a significant degree of flexibility by individuals in dealing with the problem domain in which novelty is the norm.

- **Systems Thinking**

Bertalanffy (1968) stated that systems thinking plays a dominant role in a wide range of fields from industrial enterprise to esoteric topics of pure science. Checkland (1999) provided a useful definition of systems thinking (Table 2.9, chapter II) that will be used as a cornerstone for this research:

"An epistemology which, when applied to human activity is based upon the four basic ideas: emergence, hierarchy, communication, and control as characteristics of systems. When applied to nature or designed systems the crucial characteristic is the emergent properties of the whole" [Checkland, (1999), p. 318].

For the purpose of this research, systems thinking is used to describe the language and design to address complex problem domains.

- **Systems Thinking Characteristics**

The domain of studying the characteristics of systems professionals is still in the early stages (Frank, 2006). Frank (2006) has presented a comparison of three different studies (Frank, 2006; Frampton et al. 2005; Di Carlo et al. 2006) exploring the desired characteristics of systems professionals including systems engineers, systems architects, and information technology (IT) architects. They found these characteristics could be classified and consolidated in four primary areas:
(1) cognitive characteristics, (2) abilities characteristics, (3) knowledge and background characteristics, and (4) personal traits.

The perspective taken for systems thinking characteristics for this research is taken as the set of abilities, preferences and skills characteristics that individuals exhibit in dealing with a complex problem domain.

LIMITATIONS OF THE RESEARCH

This section addresses the main limitations concerning the present research endeavor. The main limitation of the current research is that the proposed research instrument is new, and there are no current techniques or tools with which it can be compared for a 'validation' in the true sense of external validation.

The proposed research instrument is completely new. There is no similar tool or method that can be used as a point of reference for comparison. As mentioned earlier, there are insufficient tools and techniques purposefully designed to deal with complex problem domains. At best, there are emerging methodologies (Adams and Keating, 2011) and selection of existing tools from related fields (e.g. stakeholder analysis, objectives tree, etc.). Thus, this imposes a limitation with respect to the establishment of external validation for the 'new' instrument, as it has no other reference point against which it can be gaged.

Another limitation of this research is the use of a personality theory based instrument as a surrogate (Myers -Briggs Type Indicator). In fact this limitation has no effect on the current research because MBTI used to provide inputs for future research. The personality theory literature is a dense field. Thus, while the systems thinking characteristics mapped to the MBTI (Appendix F) the current research was not intended to make inference or contribution to personality theory. The only purpose of the mapping process was to provide inputs to study the correlations between personality profile and systems thinking profile in the future. As such, the researcher conducted a preliminary scan of the literature on personality, trait theories, type theories, and cognitive theories, as they are representative of some theories pertaining to the study of personality. For this research, personality theory was beyond the scope of the inquiry. Therefore, since the research was not about examination of personality type, the MBTI was used strictly to map and link systems thinking characteristics (Appendix E). Although interesting topics, the research makes no claims concerning either: (1) the relationship of personality type to systems thinking, (2) contributions to the personality type field, or (3) extension of systems thinking into the personality type field.

Below are the strategies that the researcher has developed to provide a responsive research design based on limitations:

- Since the proposed systems thinking instrument is new to the field, phases II and III were developed for validity and reliability based on the current state of knowledge. In addition, the researcher conducted factor analysis and Monte Carlo simulation to test the validity and reliability of the new systems thinking instrument.

- Exploratory factor analysis and Monte Carlo Parallel analysis were conducted to test and examine the degree to which the systems thinking instrument provides a level of validity and reliability, but it is limited by the first instantiation of the instrument for testing.

SUMMARY

This chapter has explained the significance of this research and the anticipated contributions across theoretical, methodological, and practical dimensions. To achieve the purpose of the research, two main questions were addressed to support the scope of the research (Figure 1.1).The structure of the inquiry works as boundaries that shaped the scope of the research. After presenting the research significance, purpose, questions, and terms/definitions the chapter paves the way for the next chapter. The next chapter will present the background literature supporting this research. This literature is organized around three major streams including, complex systems/System of Systems (SoS), system theory, and systems thinking.

CHAPTER II

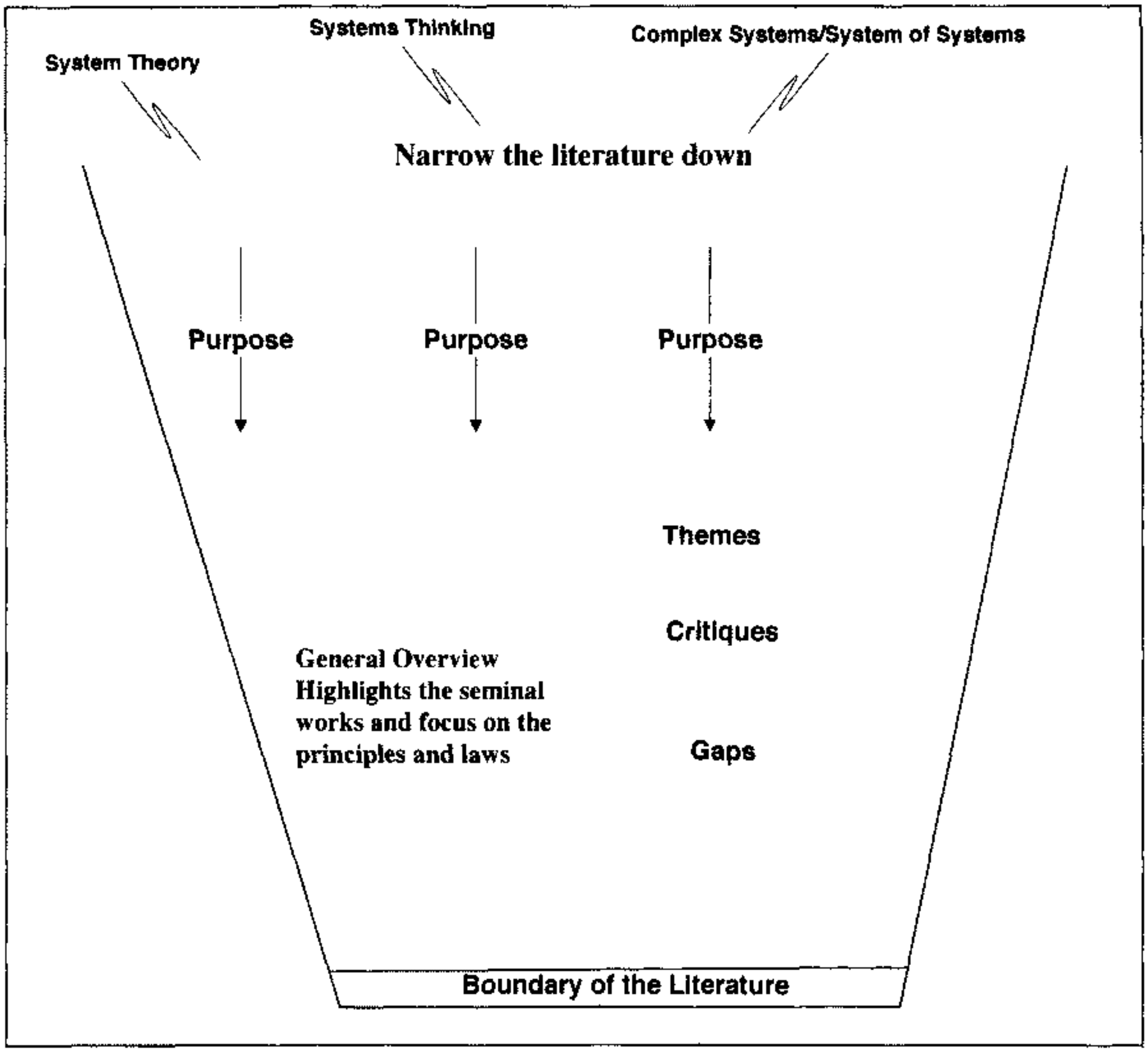
LITERATURE REVIEW

The purpose of this chapter is to set up the foundation for the research, define the scope of literature for review, and to establish the relationship of the present research within the larger body of knowledge. In the development of the literature, the researcher focused on achieving several objectives. First, the literature review schema is identified. Second, a thorough review of three primary streams of literature are reviewed, including system theory, complex systems/SoS, and systems thinking. Third, the current themes of the literature were identified. Fourth, a detailed critique of the literature was conducted. Fifth, the main gaps in the literature were explored through rigorous scholarly consideration. Finally, the researcher summarizes the map of the literature to illustrate the position for this research as an original contribution to the complex systems field.

LITERATURE REVIEW SCHEMA

The background literature supporting this research consists of three main sections: system theory, complex systems/SoS, and systems thinking (Figure 2.1).

Figure 2.1: Background Literature of the Research



The first section for review is systems theory, which starts with a general overview on system theory then highlights the seminal works related to system theory. The purpose of this section is to show how system theory encompasses the underlying theoretical foundation to better understand complex problem domains and why system theory is valid for all systems. Providing detailed discussions of system theory is beyond the scope of this research. The second section is complex systems including SoS which considers the focal point in the background literature supporting this research. Stemming from an extensive review of complex systems, a detailed discussion of the themes, critique and gaps is presented. The aim is to explain why traditional systems engineering tools and methods have not enjoyed the same level of success when applied to complex problem domains. The last section is systems thinking, which starts with a general review of systems thinking then highlights the pioneering works in this field. The intent of this section is to show the specific role systems thinking plays in understanding complex problems domains.

SYSTEMS THEORY

System theory is the first thread in the development of the literature (Figure 2.1). Over decades we have witnessed a rapid growth in technology that forced humans to deal with innumerable problems and complexities. Dealing with complexity and the associated problems is a reality. Bertalanffy's (1968) explorations in general systems theory exemplified that the progress and improvement in fields such as social sciences and biology suggested that the applications of existing sciences, such as physics, were insufficient to provide more universal language and laws that crossed multiple fields with a much more universal applicability. In fact, general system theory was developed before other related fields such as cybernetics.

HISTORY OF SYSTEM THEORY

Ludwing Von Bertalanffy is considered the father of system theory, but there are several related works and theories that had been completed prior to his seminal efforts. These works did not mention general system theory directly; however, they pointed out the importance of general system theory (GST) and might certainly have been foundational forerunners to the emergence of von Bertalanffy's work. Kohler (1924) pointed out the need for general system theory, but it was restricted to the field of physics. Kohler "raised the postulate of a system theory, intended to elaborate the most general properties of inorganic compared to organic systems." [Bertalanffy, (1968), p. 11] The theory of formal organization appeared in sociology. This theory is reframed from a philosophical scholar who mentioned that it is imperative to study an organization as a system to gain a better understanding of the structure of an organization (Scott, 1963). Thus this theory leads into the discussion of general system theory. In (1925) Lotka came closer to the discussion of system theory. He attempted to treat systems in general without restrictions to any field.

In (1964), Boulding postulated five points for developing general system theory (GST) in terms of order. In one of these points he mentioned that to avoid chaos in systems, it is better to establish some common variables. Bertalanffy (1968) portrayed the idea of having a general system theory for all systems. He provided a universal language and laws that crossed multiple fields with a much more universal applicability. Some highlights of von Bertalanffy's perspective include:

- The inability of many mathematical models in physics, chemistry and other fields to adequately capture the nature of phenomena. Concepts such as wholeness, control, etc.

occur in various fields where these concepts are alien in mathematical models. In social sciences such concepts are prevalent and exist beyond the capability of mathematical models to address.

- The move towards generalization makes it necessary to think in new ways such that a theory to capture general principles for all systems, regardless of the nature of the system, might be developed with a level of universality. This was the basis for Von Bertalanffy's development of the novel field he called "General System Theory".
- Similar approaches and models appeared synchronously in many disparate fields. Von Bertalanffy posited that there were many identical principles appearing in different fields and that system theory could integrate this knowledge to avoid unnecessary duplication and ambiguities between fields.
- Some physics and mathematical laws had become inadequate to understand, describe, or explain the increasing complexity of systems.
- In social sciences there are many problems that need new tools and methods to be solved. Physics and mathematical models have not succeeded in solving social-technical problems.

MOVEMENTS IN SYSTEMS THEORY

A trend towards generalized theories in biology, physics, psychology, social science, and other fields has appeared. This postulates the legitimacy of having valid general principles for all systems. In the 1940s general system theory was new and became popular. Presentations, conferences, symposiums and journals flourished in such publications as the *Mathematical System Theory Journal*. In (1954) the International Society for General Systems Research (ISGST) was launched. The founders of this society are Bertalanffy, a biologist; Ralph Gerarad, a physiologist; Anatol Rapoport, a mathematician; and Kenneth Boulding, an economist. Later, this society became known as the International Society for System Sciences (ISSS). The primary role of this emerging systems research was "to investigate the isomorphy of concepts, laws, and models in various fields, and to help in useful transfer from one field to another" [Bertalanffy, (1968), p.15]. Thus, the development of general system theory was intended to be a language and set of universal laws that would be applicable independent of the particular field within which they might be applied. Skyttner (2001, p. 37) mentioned that system theory is not a new discipline; however, "it is a theory cutting across most other disciplines linking closely e.g. generalized concept of organization, to that of information and communication."

Following the notions of general systems theory, different theories emerged that were consistent with the tenets and mutually supportive of general system theory. Some of these theories certainly caught on, including: cybernetics theory (Norbert Wiener, 1948), game theory (Neumann and Morgenstern, 1947), information theory (Shannon and Weaver, 1949) and net theory (Rapoport, 1949). The impact of cybernetics theory has been carried over into many diverse disciplines, including extrapolation to the social sciences. While there is certainly an argument to be made for the separation of cybernetics from system theory, their overlap and influence in the SoS field is evident for some quarters of the emerging development of the field. Review of the development of these theories in detail would pre-empt the consideration of this research, so this dissertation mentions only the ones (cybernetics theory and Viable System Model) related to the current research.

There is a misunderstanding regarding cybernetics theory. Some argue that system theory can be identified as cybernetics. In fact, this is incorrect; cybernetics theory is just a part of system theory. Bertalanffy (1968, p.21) said that cybernetics is a "theory of control systems based on transfer of information between system and environment and within the system, and control (feedback) of the system's function in regard to environment." Negative or positive feedback is the main element of cybernetics. This feedback helps systems to tackle unexpected events that might occur after systems operate. The feedback plays a necessary role in the structure of systems. The impact of cybernetics theory has been carried over to many diverse disciplines, including extrapolation to the social sciences.

The Viable System Model (VSM) is a methodology that deals with complex systems (Beer, 1981). The aim of VSM is to understand the structure analysis of complex system problems. Thus, there are five functions or system components (S1-S5): productive function, coordination function, operation function, development function, and identity function. The idea of these functions is to keep systems viable and provide a language of thinking that crosses multiple domains of application. One of the main elements of VSM is communication. Beer identified seven communication channels that move information among system entities. The communication channels in VSM are command, accountability, operation, coordination, audit, algedonic, and environmental scanning channels. These system components and channels are necessary for any complex system to remain viable.

A significant contribution to the GST came from Bowler (1981). He mentioned that all systems, no matter how diverse, have some common characteristics. He used the term "universe" to synthesize "system of systems and disintegrating systems of systems" [as cited in Skyttner, (2001), p.32].

SYSTEM THEORY AND TRADITIONAL SCIENCES

Systems Theory, in contrast to traditional views of physics based science, rejected the notion of addressing problems by reducing them into units and studying each element in isolation – traditional reductionism. Although reductionism has had success in dealing with simple systems and physics based relationships, the appropriateness of this paradigm for application to the complexities of modern day systems has been questioned extensively (Senge, 1990). The principle of classical science, "the whole is more than a sum of its parts" from philosopher Aristotle, was widely known until the Scientific Revolution of the 19th century. Although this principle has had success in dealing with systems that have weak or simple interactions between entities and the relationship among them is linear, the appropriateness of this principle for application to systems that have wicked interactions among entities and nonlinear relationship has been questioned.

In response to reductionist thinking and classical science principles, Bertlanlanffy (1968) positioned the role of system theory as providing more general principles that can be applied holistically and with a degree of universality across all systems, natural or manmade. This assertion was in stark contrast to the prevailing sentiments of the reductionist perspectives taken by the classical science approach. The principal aim of system theory is to "state principles which apply to systems in general…even its particular nature, parts, relations, etc., are unknown or not investigated" [Bertalanffy, (1968), p.19].

It is essential to mention that Smuts (1926) is the first to use the term "holon" (holism) in his well-known book (*Holism and Evolution*). Later, several researchers postulated the importance of moving to holistic approaches.

The following example shows how some physics laws disappeared or have been neglected with the increasing complexity of systems. In closed systems which are considered to be bound off, the environment entropy works well. Entropy, the second principle of thermodynamics, is the measure of disorder in the system. Closed systems tend to maximize their entropy, so there is randomness. When entropy tends to maximize their disorder, the system becomes static. There is no more energy, or exchange will happen within the system. However, in an open system entropy becomes negative. Adding structure and order to the system from the surrounding environment will affect the randomness in the system. Thus, system theory came to deal with such issues.

SYSTEM THEORY AND COMPLEX SYSTEMS/ (SoS)

Proceeding from the arguments in support of systems theory, Adams and Keating (2011, p.11) suggest that "system theory encompasses the underlying theoretical foundation for understanding systems". This system theory foundation is critical to understanding and dealing with complex systems. Therefore, this underlying worldview of systems is suggested as essential to engagement of the complexities inherent in the SoS problem domain. It is imperative to better understand the fit of individuals to the general principles and laws which form the essence of the holistic systems perspective –

or systems thinking. Thus, the role played by system theory in this research is to draw the underlying linkage between the constituent principles of system theory as appropriate for complex problems domains. True to the tenets of systems theory, this research is focused on development of this linkage through understanding the principles and laws that underlie all systems, regardless of the nature of the system.

Systems Engineering is considered the foundation of SoS. "Among the strengths of systems engineering that SoS must draw upon are: first, the linkage to systems theory and principles for design, analysis, and execution, second, interdisciplinary focus in problem solving and system development and third, emphasis on disciplined and structured processes to achive results." [Keating, et al. (2003), p.40]

The aim of GST is to describe systems with general laws and principles. Skyttner (2001) proclaimed that to understand complex systems, it is necessary to understand the foundation of GST which helps to apply a systems thinking paradigm. In the section to follow, the researcher examined the history of complex systems. The purpose of the history is to : (1) identify the common themes and perspectives, (2) provide detailed criticism of the literature, (3) identify the main gaps, and (4) position this research as a unique contribution to the literature.

The research concept of system theory and systems thinking focuses primarily on the principles and laws that are necessary to understand complex problems. Listing these principles and laws in detail would preempt the consideration of the research. These principles and laws are compiled by Skyttner (2001, pp.92–96) and Clemson (1984, pp.199–257).

COMPLEX SYSTEMS/SYSTEM OF SYSTEMS

This is the second thread in the development of the literature (Figure 2.1) which represents the focus of the research. In this section a histogram analysis is constructed to understand the development of complex systems/SoS.

There are multiple definitions, characteristics and methodologies pertinent to the body of SoS. Throughout the short history of SoS there have been many terms used to describe what today is called "system of systems". The current state, as well as future directions for the field, can be informed by exploration and appreciation of where the SoS concept emerged as well as the shape of the distribution for its development.

This section synthesizes the variety of commonly cited definitions, characteristics, and methodologies of complex systems by tracing the history of development for the SoS field. This section is focused on the conceptual development of the SoS domain as evidenced through the published literature of the field. The existence of the array of definitions and perspectives of SoS is not a criticism of the field. On the contrary, it suggests that the field is early in development and continues to embrace a variety of formulations, each adding value from a particular perspective and conceptual development as well as appropriateness for utility in a given context. In fact, "a variety of perspectives is a powerful resource in dealing with a dynamic environment because it is not possible to anticipate which perspective will be needed for some new set of conditions" [Clemson, (1991), p.206].

The researcher has traced the history of SoS from 1926-2011. To do this the researcher has reviewed and analyzed over five hundred different resources including peer reviewed journal articles, peer reviewed conference proceedings, books and book chapters and then constructed a histogram to display the shape of distribution for the evolving SoS history. The object of the histogram is to: (1) determine the significant contributions to the body of SoS knowledge (2) show the peak knowledge production in the development of the SoS field, and (3) display the relative frequency of the SoS history into class intervals.

There are two fundamental questions that must be asked in considering applicability of SoS to a particular problem domain. First, 'what is a SoS'? While this seems straight forward, as seen in the literature, the answer is far from straightforward and has implications for the appropriateness of the SoS frame of reference to address complex problems. Second, 'what are the characteristics or attributes that are most essential to describe a SoS'? In SoS a helpful perspective is that, if you cannot understand what a SoS is, you cannot deal with it'. A deeper examination of these questions might be informed by understanding the historical development of the SoS field. The essence of the still maturing SoS field is held in the potential ability of SoS based approaches to more holistically address complex system problems marked by increasing complexity, excessive information, ambiguity, emergence and high levels of uncertainty.

Dealing with problems exhibiting these characteristics requires knowledge of not only technological issues but also of the inherent human/social, organizational/managerial, and political/policy dimensions that developers of solutions would be well advised to consider. While there is nothing approaching concurrence on the nature and meaning of the field, SoS has certainly recognized the need to holistically examine complex problem domains.

Since it is difficult, if not impossible, to include all the research and works regarding complex systems/SoS, the researcher developed criteria that guided the selection of materials for inclusion. Central to this criteria were selection of those that contributed most to the field as evidenced by the frequency of citation for the work. The researcher is confident that, while not all works are included, the insights generated from the analysis are representative of the field as a whole. It is important to mention that the researcher did not provide detailed discussion for all the references, but all the 500+ resources are included in the analysis. Nvivo software (QSR International, Version 10, 2014) was used to support the cataloging, organizing, and synthesizing of the set of data (over 500 different resources) used in the analysis.

In the section to follow, the researcher provided a description of the construction of the histogram analysis (providing an organization of literature) and showed some of the main contributions to the body of SoS.

HISTOGRAM ANALYSIS CONSTRUCTION

As with any analysis, the researcher began by setting the boundaries for what would be included. The researcher has selected the following criteria to bound inclusion in the histogram analysis: (1) definitions for complex systems/SoS, (2) characteristics for SoS, (3) methodologies for SoS, and (4) principles and axioms for SoS. It should be noted that the histogram analysis is not organized or differentiated by the different application domains for SoS (e.g. healthcare, transportation, defense, critical infrastructure, etc.). This level of analysis, while interesting, is beyond the present scope of coverage for this research effort.

To construct a histogram analysis, the first issue was to determine the range- the difference between the largest value and the smallest value in the data. Since the researcher has traced this concept from 1950 until 2011, the range is 61 years. This coverage provides a historical context, dating back to the earliest beginnings of the forming SoS field. The next step was to divide the range into intervals (classes). In statistics, there are some rules of thumb used to determine the number of classes in a histogram. The most important rule is to have almost equal widths for each class for a better visual description of the data. Therefore, the researcher identified 3 main intervals classified as shown in Table 2.1. A chronological order to show the history of SoS has been used.

Table 2.1: Interval Classifications

Intervals for Histogram	
1950-1969	1
1970-1989	2
1990-2011	3

The object of constructing a histogram (Figure 2.4) is (1) to obtain quantitative information about the shape of distribution for complex systems/SoS history from 1950-2011 focused on determining the peak of the development of SoS and (2) calculate the relative frequency for each interval which shows the activity for contributions in the development of SoS. The horizontal axis in the histogram represents the number of years (classes), and the vertical axis represents the frequency and relative frequency of contribution activity for each class. After identifying the main intervals, the next sub-sections discuss each interval in detail.

INTERVALS (HISTORY OF COMPLEX SYSTEMS)

This subsection discusses the three main intervals in the literature. Three intervals were established to trace the history of SoS. The first interval is from 1950-1969, the second from 1970-1989 and the last one is from 1990-2011. For each of the intervals the researcher identified some of the major contributions to the body of SoS. It is important to mention that these intervals did not provide detailed discussion for all the references, but all the 500+ resources are included in the analysis. Nvivo software is used to organize the set of data (500 different resources) in the analysis.

Interval 1 from 1950-1969

After reviewing the literature within this interval, the researcher found that the earliest roots to SoS can be found in Smuts (1926). He is the first to use the term "holon" to describe the "whole and the parts of a system". In the last two decades, the perspective invoked from this term is considered one of the characteristics of system of systems. Boulding, in his book 'General Systems Theory - the Skeleton of Science' (1956), emphasized that there is a need to move away from pure mathematical techniques and to shift our thinking to better understand complex systems. He suggested the "theoretical systems hierarchy of complexity" [Boulding, (1956), p. 202]. In the hierarchy the degree of complexity varies from level 1 to level 9 where level 1 represents a static system and level 9 the most complex structure. He used the term "gestalt" to describe what we would presently refer to as a SoS. Simon (1955-1956) asserted that achieving optimization in a turbulent, complex, and dynamic environment is a daunting task. Instead, he suggested *satisficing* "good enough" solutions are most appropriate. Ranging through 1950 to 1959 the researcher found that the trend was on recognizing the nature of complex systems and there was no definition or perspective that specifically describes SoS. However, the researcher can ascertain that the 'systems movement' and recognition of the difference in complexity and levels of systems was in full formulation.

The earliest definition of SoS can be found in Berry (1964) where he described cities as 'systems within systems'. Von Bertalanffy (1968) is considered one of the systems theory pioneers who challenged the efficacy of reductionist approaches in complex systems. He portrayed the idea of having a general system theory for all systems. He provided a universal language and laws that spanned multiple fields with the goal of universal applicability. In section one (systems theory) the researcher highlighted some of his perspectives which, both directly and indirectly, have influenced the development of the SoS field.

Following the notions of general systems theory, different theories emerged that were consistent with the tenets and mutually supportive of general system theory. Some of these theories certainly caught on, including: cybernetics theory (Norbert Wiener, 1948), game theory (Neumann and Morgenstern, 1947), and information theory (Shannon and Weaver, 1949). The impact of cybernetics theory has been carried over to many diverse disciplines, including extrapolation to the social sciences.

A survey of the literature from (1960-1969) shows that: (1) late in the 1960s the focus toward holistic approaches to deal with increasingly complex systems, and their constituent problems, became apparent, (2) there was an early glimpse of the evolution of complex systems and corresponding level of thinking, and (3) there was only one definition for SoS. Although the term SoS itself was not used at this time, the need for improvements and development to address complex system problems accelerated. The researcher labeled this interval Recognition of Complex Problems (Figure 2.2). Table 2.2 shows the main critical themes for this interval.

Table 2.2: Main Themes for the 1950-1969 Interval

Critical themes for the first interval
• The term "holon" has been introduced which eventually support a major tenet in SoS
• Recognition of the difference in complexity levels
• One definition of SoS was introduced
• Limitations of the traditional reductionist approaches in complex problems were recognized
• The idea of general system theory was introduced

Interval 2 from 1970-1989

Following Von Bertalanffy's proposal for GST, Ackoff in (1971) challenged the idea of analyzing systems by breaking the systems into parts. Instead, he proposed that the focus should be on treating the systems as a whole. Ackoff believed that the interactions among entities within systems are aggregated and dependent on one another.

Therefore, reductionist approaches were not deemed adequate in understanding these interactions. Furthermore, Ackoff identified many shortcomings and limitations in reductionist approaches whenever they are applied to real life complex situations. Ackoff used the term "integrated set" to describe what we would come to call SoS as "a set of interrelated (or integrated) elements" (p. 662). A concrete system is an example of a complex system where the relationships between the elements can be traced with a high level of confidence. A system should consist of at least two elements with direct or indirect relationships between the elements or the sub-elements (Ackoff, 1971). While Ackoff did not directly propose SoS, his thinking was foundational as he questioned the traditionally held reductionist approaches to dealing with systems. This thread would continue and be foundational to the evolution of the SoS field.

In 1975 Weinberg, among other authors, (Checkland, 1993; Beer, 1979) also recognized the limited capabilities of traditional systems engineering (TSE) to deal with real world complex problems. They asserted the need to move toward more holistic approaches. Several authors asserted the need to deal with the increasing complexity in systems and to move beyond traditional SE processes and practices toward a more holistic paradigm (Flood and Carson, 1993; Beer, 1979; Checkland, 1993; Weinberg, 1975). This early break, suggesting the limitation of addressing complex systems and their problems from a purely reductionist (technical) perspective, was instrumental to an evolution toward more 'holistic' considerations for the SoS field.

In (1972) Beer introduced the term "metasystem" to describe the integration of systems using a cybernetic perspective. Beer made a significant contribution to understanding the structure of a complex system. He developed the viable system model

(VSM), comprised of five main functions necessary to assure the viability (continued existence) of a complex system. These functions together provide a better understanding of the interactions among entities. These five functions included: (1) the *productive* function which produces the output of the system, (2) the *coordination* function which provides coordination among the subsystems to prevent oscillations in the system, (3) the *operation* function which is responsible for the operational decisions in the day to day concerns of the system, (4) the *development* function which scans and explores the surrounding environment and ensures that the system is properly poised to continue existence into the future, and (5) the *identity* function, the last function in the VSM, which links the preceding functions together and provides the vision, mission and purpose of the entire system. Beer also provided insight into required communication channels in complex systems. Beer's model is instructive "for effectiveness in SoS communications to deal with emergence." [Keating, (2009), p. 184]. While Beers contributions to SoS are not necessarily mainstream in references to SoS based development, it provided an important cybernetic foundation that has been significant in some corners of development for the SoS field.

Jackson and Keys (1984) explained that pluralism is a concept at the individual and enterprise levels and acknowledged that the multitude of different methodologies for addressing complex systems problems could be conceptualized in a 'system' of 'systems methodologies' categorization framework. They based classification of different systems-based methodologies and the particular approach advocated in relation to real world problems. They categorized systems methodologies according to distinctions as ranging from *unitary* (there is an agreement on the set of goals) or *pluralist* (pursuit of multiple, potentially divergent, objectives). Unitary assumptions are appropriate when the problem context is relatively well bounded (simple system) and can be solved using a deterministic approach or model. In unitary problem contexts for simple systems, SE tools and/or techniques are appropriate. In contrast, system of systems problems are more pluralistic in nature where there is not necessarily agreement on a common set of goals and cannot readily be considered to be simple systems.

In the same year Clemson (1984) emphasized the importance of multiple perspectives (emphasizing the complementarity principle from cybernetics). In 1986, Perrow made a notable contribution by studying the unexpected events of large complex systems. While there was still not direct references being attributed to SoS, it is easy to see the 'uneasiness' that was developing with traditional reductionist approaches and their limitations for addressing an emerging class of problems. Although not directly attributed to the 'SoS' problem domain, the limitations to traditional approaches were being firmly set.

A survey of the literature within this interval (1970-1989) demonstrates that: (1) there was a necessary need to shift beyond traditional reductionism based thinking and approaches to address complex system problems, (2) the notion of system of systems was acknowledged, sometimes indirectly, (3) there were some definitions and perspectives of SoS that focus on treating the system as a whole beginning to emerge, and (4) some systems-based methodologies to address the emerging SoS problem domain had been proposed. Although there was recognition of SoS, there was limited research on SoS in terms of definitions and characteristics, with much of the developing literature indirectly acknowledging SoS. The researcher labeled this interval as Exploratory of SoS. Table 2.3 shows the main themes in this interval.

Table 2.3: Main Themes for the 1970-1989 Interval

Critical themes for the second interval
• Focus on the whole, rather than isolated elements
• Limitations of traditional systems engineering (TSE) in addressing complex problems
• The need to move toward holistic approaches to deal with increasingly complex systems and problems
• Indirect acknowledgement of SoS, without direct use or definition of the term
• Some perspectives and methodologies capable of addressing SoS problems were in the formative stages

Interval 3 from 1990-2011

This interval witnessed the revolution of SoS especially in the second decade (Figures 2.2 & 2.4). Several perspectives and articulations were presented, and the field was in full development during this period. Many studies and works attempted to distinguish SE from SoS characteristics. Several studies focused on such wide ranging topics such as integration versus autonomy, optimizing versus "*satisficing*" solutions, complex systems versus single systems, holism versus reductionism, technical problems versus socio-technical problems, multiple perspectives versus single perspective, centralization versus decentralization, the goal of pluralistic versus unitary, turbulent environment versus static environment. Presentations, conferences, symposiums and journals with respect to complex problems/SoS flourished, including initiation of an IEEE annual conference titled System of Systems Engineering. In this interval the researcher found that several studies and works appeared to emerge around the following perspectives:

(1) Definitions and types for SoS,

(2) Characteristics for SoS,

(3) Methodologies, approaches, and tools for SoS, and

(4) Foundational principles and axioms for SoS.

The following shows the major contributions in each category.

First Category: Definitions and Types of SoS

This category identifies some important works that provide definitions and types for SoS. Senge (1990) asserted the importance of the whole by stating that breaking problems into discrete manageable elements then proceeding to solve each elemental problem is an insufficient concept when applied to real life situations. Following Simon (1955-1956), Richardson (1991) proclaimed the idea of satisficing solutions by using the term "Synthesis" (satisficing). Further still, Mitroff and Linstone (1993) proposed employing holistic approaches versus reduction, suggesting that future techniques should involve multiple perspectives, to include as much of the 'richness' of the situation as possible, and recognition of the enormity of interactions that exist in social-technical systems. In 1995, Ackoff developed "the 'system of systems' concept by defining the elements of a system and the changes that occur within them." [as cited in Clegg and Orme, (2012), p. 59]. Northrop et al. (2006) mentioned that large scale systems should be taken as a whole to satisfy a specific mission. In the same vein, Jamshidi (2009b) labeled control as one of the main issues for SoS. He presented different types of control paradigms for SoS namely hierarchical, decentralized, consensus, cooperative, and networked controls.

Another definition came from Eisner (1993) who described SoS as "large geographically distributed assemblages developed using centrally directed development efforts in which the component systems and their integration are deliberately, and centrally, planned for a particular purpose." [as cited in Wells and Sage, (2008), p. 49]. From a different perspective, Shenhar (1994) described SoS as a network of systems. The purpose of this network is to accomplish a common purpose. The diversity of perspectives, but seemingly congruent threads, marked acknowledgement of the need to integrate multiple systems into something beyond the simple aggregate of individual systems.

Owens is considered the pioneer in the use of the term SoS in military application. In 1996 he asserted that SoS alleviated some of the military issues that traditional system engineering practices were incapable of resolving. SoS also provided new capabilities that would be helpful in increasing the ability (now and in the future) of defending and understanding the messy and chaotic complex situations, suggesting they could "Reduce the fog and friction of conflict opponents" (p.4) In the same year, Manthorpe (1996) used the term "jointness" to link and describe SoS.

In 1997 Kotov introduced a term "large scale systems" which are complex systems themselves. Lukasik, (1998) mentioned that SoS Engineering involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure (as cited in Lane and Valerdi, 2007b). It is evident that these formulations directed SoS to the entire range of issues, technical and nontechnical, related to integration of multiple 'existing' systems into larger systems of systems. Krygiel (1999), based on two case studies (National Imagery and Mapping Agency and U.S. Army), extrapolated some lessons that supported categorization for SoS. Krygiel provided a "classification of systems that shows the relationship between conventional systems, system of systems, and federations of systems" (p.328). He described SoS as a group of individual complex systems connected together to produce a new behavior which is not achievable by the individual systems. In an analogous perspective, Crossley (2004) described SoS as the integration of a mix of multiple large scale systems that must interact together to achieve a generic goal.

From 1998-2001 the definition of SoS began to take on a new shape with emphasis on the types of SoS as described by Allison and Cook (1998) and Cook (2001), suggesting that there are two types of SoS: dedicated SoS and virtual SoS. Dedicated SoS are large complex systems which are themselves comprised of individual constituent large systems working together to accomplish a specific need. In contrast, virtual SoS (Owens, 1996) fits military environments where multiple complex systems need to integrate (but were never designed to be) to accomplish an emergent mission. A good example is a command and control (C2) system for a coalition peacekeeping operations (Cook, 2001). Dedicated SoS is a ground-up systems (planned integration). In contrast, virtual systems are unprepared for integration (Cook, 2001).

From an historical perspective, the evolution of SoS was accelerating, with the definitions taking shape and differentiations appreciating different 'types' of SoS emerging. In 2001 there were two main contributions from Sage and Cuppan and Cook concerning SoS. Sage and Cuppan emphasized that "modern systems are not monolithic" (p. 326); rather, they follow notions of federalism. "Enterprise Systems Engineering" (ESE) is the term that Carlock and Fenton used to describe large complex SoS.

An interesting definition of SoSE can be found in Keating et al., (2003). They defined SoSE as "The design, deployment, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results. These metasystems are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography, and conceptual frame." (p 40) On the other hand, Hitchins (2003) mentioned that in fact a SoS is just a system, and there is no one unique definition for SoS. For the SoS field, despite the agreements on complex system problems not being adequately addressed, the fragmentation in different perspectives and formulations of SoS in response was emerging.

In 2004 Bar-Yam and his interdisciplinary group offered additional characteristics of SoS (i.e. self-organization, synergy, and individual specialization) that should be included in a more comprehensive and generalized definition. According to Bar-Yam et al., Sage and Cuppan's (2001) definition is the most appropriate one among others, but still there is a need for a more comprehensive definition. It is noteworthy to mention that these comprehensive characteristics arose from three primary domains: biology, sociology, and the military. From a biological perspective, SoS is a struggle between the autonomy of individual systems and the need for interdependency from membership in a larger entity. From a social point of view, the individual systems voluntarily integrate to constitute a SoS. From a military point of view the integration increases the effectiveness among the individual systems.

Delaurentis, (2005) added the term "trans-domain networks of heterogeneous systems" to the taxonomy of SoS. Again, the fragmentation of the SoS field was evident during this period. This is not a particular criticism of the field but a recognition that with increasing attention a corresponding increase in variety of perspectives should be expected. In the early development of a field, this diversity of perspectives is not a deterrent. Instead, it is healthy to resist the urge to quickly narrow the field and resist the possibility of excluding potentially new and insightful discoveries.

A major contribution to the SoS field came from Maier (2005). He defined SoS as a collaborative network-centric assemblage. He classified the collaborative SoS network into three categories (1) *closed control* where the Lead System Integrator (LSI) controls the elements of the SoS; (2) *open control* where there is control but it is limited; and (3) *virtual* where there is no control. He portrayed that the research problems and challenges associated with SoS are not the same as those associated with conventional systems. The first challenge is the social and technical problems inherent in SoS. The second challenge is that current methods show weaknesses dealing with the messy interaction among the network elements of SoS (upper layer). The third challenge is with regard to optimization.

In SoS, true optimization is not achievable since there are many possible solutions that can provide an acceptable design solution. The last challenge is the uncertainty and limited central control in SoS. Even though the SoS works did not make a direct linkage to the earlier criticisms of traditional systems engineering based approaches, they illuminated the inherent need for formulations of the SoS problem domain to reach beyond the purely technical aspects of complex system problems.

According to Kovacic et al., (2006) the best way to define SoS is based on the complexity level of the situation. They viewed SoS as wicked problems. These wicked problems have unique characteristics not found in the characterization of a traditional problem approachable from established methods. Wojcik and Hoffman (2006) treated SoSE as an element of enterprise activities to deal with complex systems. Delaurentis et al. (2006) developed a three-phase approach for SoS namely, definition, abstraction, and simulation phases. These phases work in concert to help the investigator understand the technical and social components in SoS. The first phase is to define the SoS problem with its context. In the second phase the inputs are identified and mapped (people, things, and others) and the last phase is for simulating the inputs and providing decisions. This is an interesting formulation that amplifies the preoccupation of this SoS time interval with defining approaches to deal with SoS problems.

An interesting definition of SoS came from Sahin (2007a, 2007b) who described SoS as heterogeneous systems working together to produce capabilities that are not conceivable by traditional systems. He defined SoS as "large-scale concurrent and distributed systems that are comprised of complex systems." (p.1376) An analogous definition by Azarnoush et al. (2006) mentioned that SoS are comprised of heterogeneous, large independent systems. Similarly, DiMario et al. (2008) explained that system of systems (SoS) are comprised of large, numerous constituent systems. The heterogeneity of these individual systems produces unintended consequences that do not originate from any one individual constituent system. Again, there is a constant need to 'define' SoS. Interestingly, although the definitions vary, there was some emerging commonality, and even some easily traced roots to the origination and development of the early systems movement.

Sousa-Poza et al. (2008) emphasized that SoSE needs to be considered as a meta-discipline approach. Therefore, they identified several ontological conditions pertinent to SoSE as well as some methodological attributes. An important contributor to the development of SoS is Jamshidi (2008) who compiled two main books dedicated directly to the field of SoS. In these books he provided several definitions and detailed literature reviews of SoS. Heterogeneous, large-scale, independent, network are the terms Jamshidi used to describe SoS. However, it should be noted that the works on SoS were focused on a 'collection' of perspectives and some applications, not on the underlying conceptual or intellectual foundations for the field.

McCarter and White (2009) provided some treatments for the unexpected behavior (emergence) in complex systems engineering which include and describe SoS. This emergence occurs because of the integration of multiple autonomous individual systems. This integration does not only include systems but also multiple perspectives (human cognition and perception). Similarly, Clark (2009) clarified that SoSE is not a technical problem. If it is, it can be solved using SE processes. Instead, it is a managerial problem in terms of integrations and acquisitions. Lane et al. (2010) described SoS as a mix of individual systems gathered together to accomplish a specific need. These individual systems evolve over time. Again, the definitions and the applications of SoS are vast (Keating et al. 2003; Keating, 2005; Gorod et al. 2008). Table 2.4 below enumerates some representative definitions within the three intervals.

Table 2.4: SoS Definitions

Author	Definition/Perspective
Achoff (1971)	Considered system- of systems as a set of integrated elements of the systems concept.
Jackson and Keys (1984)	Explain that pluralism in SoSE is a systems' concept which recognizes that there may be multiple purposes/objectives at play at the individual, entity, and enterprise levels.
Eisner et al. (1991, p.125)	"A set of several independently acquired systems, each under a nominal systems engineering process; these systems are interdependent and form in their combined operation a multifunctional solution to an overall coherent mission. The optimization of each system does not guarantee the optimization of the overall system of systems."
Manthorpe (1996, p.308)	"In relation to joint warfighting, system of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR) Systems"
Maier (1998)	He defined five key principles in distinguishing large and complex but monolithic systems from true systems-of-systems. These principles are operational and managerial elements, evolutionary development, emergent behavior, and geographic distribution.
Kotov (1997, p.1)	"By system of systems (SoS) we mean large-scale concurrent and distributed systems that components of which are complex systems themselves."
Sega and Cuppan (2001)	Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development.
Keating et al. (2003, p.36)	Present SoSE as "The design, deployment, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results. These metasystems are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography, and conceptual frame.
DeLaurentis (2005, p.12)	Describes SoS as "a collection of trans-domain networks of heterogeneous systems that are likely to exhibit operational and managerial independence, geographical distribution, and emergent and evolutionary behaviors that would not be apparent ' if the systems and their interactions are modeled separately."

Table 2.4: Continued

Boardman and Sauser (2008, p.118)	Present distinguishing characteristics "(i.e. autonomy, belonging, connectivity, diversity, and emergence), that can help us to recognize or to realize a System of Systems (SoS)."
DoD (2008, p.4)	SoS systems engineering deals with planning, analyzing, organizing, and integrating the capabilities of a mix existing and new systems into a SoS.

This category has demonstrated that SoS development has had some extensive elaboration of the meaning and types of SoS. While this has provided some insightful discussions, the researcher observes:

1. Fragmentation in the variety of different perspectives put forward;
2. With very few exceptions, an absence of linking of early work in system theory or other theoretical grounding for the evolving field.

Second Category: Characteristics of SoS

The second emergent perspective the researcher found in the literature focuses on providing taxonomies and characteristics for SoS. One example is by Shenhar and Bonen, (1997) who presented 2-D taxonomy to distinguish large and complex systems from simple systems. Their taxonomy was based on two dimensions:

1. Level of complexity, and
2. Level of technological uncertainty.

They used the concept of "array" for a large and complex system (SoS): "A large widespread collection or network of systems functioning together to achieve a common purpose." (p.140). Maier (1996;1998) made a significant contribution to SoS by providing key principles in distinguishing large and complex but monolithic systems from true systems-of-systems. He mentioned that SoS are not monolithic systems because of their evolutionary development and emergent behaviors.

In 1998, Maier provided a unique taxonomic distinction, introducing concepts of operational and managerial independence as the two main properties for SoS, as well as the categorization of SoS as a collaborative system. He argued that no matter how complex and dynamic the subsystems are, without these two properties the complex system cannot be treated as a SoS. He also clarified that even though geographic distribution may be considered as a characteristic for SoS, there are many instances that showed SoS can be formed with or without the geographic distribution. In the development of SoS he suggested three categories based on control: *directed systems* (central authority), *collaborative systems* (voluntarily integration), and *virtual systems* (no central authority). He also emphasized the preceding characteristics in his book (2000) "The Art of Systems Architecting".

Many studies from several authors have followed and used these characteristics to describe SoS, and they have become somewhat of an accepted set of characteristics for the community. For example Ira and Wessel (2005), based on Maier's characteristics for SoS, mentioned that autonomy in SoS consists of operational and managerial autonomy. In the same year, DeLaurentis (2005) asserted that there are two main characteristics of SoS; evolutionary development and emergence.

In the same sense, DeLaurentis and Crossley (2005b) suggested that to design suitable methods for SoS it is necessary to have a clear taxonomy and lexicon. Thus, they proposed three-axis taxonomy based on three dimensions, namely *connectivity*, *autonomy* and *system type* for SoS. This taxonomy is a prerequisite for selection of appropriate methods. In 2008 they validated their taxonomy by providing three different transportation case studies. However, previous to this taxonomy, DeLaurentis and Callaway (2004) proposed a lexicon which serves as a prerequisite for the taxonomy. This lexicon is comprised of

1. Level of organization.
2. Four hierarchy level system categories (alpha, beta, gamma, delta).

The purpose of this lexicon is to facilitate the communication in SoS. In the same year. Gideon et al. (2005) presented another taxonomy for SoS based on

1. The problem domain of SoS.
2. Operation and acquisition of SoS.

The maturation of SoS clearly demonstrates the desire to provide clarity of terms and their usage through proliferation of taxonomies and corresponding lexicons. The unfortunate elaboration of these independently developed 'worldviews' of SoS, achieved through the language developed, did not provide a level of significant convergence for the field. This was cautioned by Keating (2005) who suggested that, while initial divergence in perspectives are constructive in the early formulation of a field, continued divergence acts to muddle the field and makes eventual convergence problematic, if not altogether impossible.

Along the same vein, Boardman and Sauser in (2006) moved from providing a definition for SoS toward distinguishing characteristics for SoS. Their noteworthy characteristics distinguish SoS from traditional systems. These characteristics are

1. *Autonomy* where constituent systems within SoS can operate and function independently and the capabilities of the SoS depends on this autonomy.

2. *Belonging* (integration), which implies that the constituent systems and their parts have the option to integrate to enable SoS capabilities.

3. *Connectivity* between components and their environment.

4. *Diversity* (different perspectives and functions).

5. *Emergence* (foreseen or unexpected).

To have clarity for development of methodologies for SoS, it is necessary to have a distinguishable set of characteristics to support classification. Thus, Bjelkemyr et al. (2007) mentioned that the characteristics of SoS are divided into two categories

1. *Boundaries* of SoS and

2. *Internal behavior* of SoS.

The former includes operational and managerial independence, geographic distribution and trans-domain applicability. The latter includes emergence, evolutionary development, and networks. To demonstrate the appropriateness of the characteristics Boardman and Sauser (2006) proposed for SoS, Baldwin and Sauser, (2009) analyzed 40 different definitions for SoS, and they determined 5 main characteristics for SoS (autonomy, belonging, connectivity, diversity and emergence). Thus, this effort does demonstrate some confluence of perspectives concerning the characteristics of a SoS.

Another major contribution came from Sage and Cuppan (2001). They used the term "federations of systems" (FOS) to describe large SoS where there is decentralized power and authority rather than centralized authority. They mentioned that systems should not be monolithic but, rather, FOS. They adopted five main characteristics to describe FOS. These characteristics are adopted from Handy (1992) and endemic to federalism. The five main principles are *subsidiarity, interdependence, uniform, separation power, and dual citizenship.* Federations of systems have the same characteristics as SoS but are:

1. "much more heterogeneous along trans-cultural and transnational sociopolitical dimensions." [as cited in Wells and Sage, (2008), p. 51]
2. Much more geographically dispersed.
3. Much more autonomous for constituent systems.

Jamshidi (2005) compiled several definitions and characteristics of SoS across several fields and perspectives. The diversity in these definitions is predictable because they are taken from multiple viewpoints. However, it does point to the continued fragmentation of the SoS field. In his book, consistent with Maier's earlier articulation, he provided five main properties for SoS:

1. Geographic distribution,
2. Emergent behavior,
3. Evolutionary development,
4. Managerial independence,
5. Operational independence.

To distinguish SoS from SE, Carlock et al. (1999) showed that in traditional systems engineering the focus is primarily on the technical and operational dimensions, while the focus on agency level systems (SoS) are on the political and economic dimensions. So the traditional SE process applied to traditional systems should be different than the process applied to SoS, due to the SoS being extended to multiple levels beyond traditional SE. In an interesting study, Cook and Sproles (2000) showed the attributes of SoS from a military perspective (i.e. autonomy, evolutionary development, large scale system, and open systems) and suggested the necessity to differentiate SoS from simple military systems, concluding that SoS requires new thinking in terms of acquisition methodologies.

Chen and Clothier (2003) provided some evolution scenarios for SoS (joint evolution, emergent evolution, and self-evolution). Each scenario requires different engineering environments. These evolution scenarios are presented as a main challenge to SE practices. Standard SE practices need to be modified, improved, and developed to accommodate SoS evolutions. Otherwise, SE practices will create additional challenges and result in a mismatch to the necessities of a SoS effort. To lessen these challenges and to advance SE practices for SoS, they proposed a three-layer paradigm (evolutionary layer, SoS layer, and organization layer).

In 2005, Ring and Madni proclaimed that the current SE practices are insufficient to deal with SoSE. Thus they asserted the need to shift the paradigm and develop a new mindset for building SoS. The consensus in the development of the SoS field was clearly supporting the claim that SoS is different that SE and that a 'different' level of thinking was necessary.

Lane and Boehm (2008) made a noteworthy contribution by presenting the different activities between the SoS lead system integrators (LSI) and traditional systems engineer. Shah et al. (2007) mentioned that what differentiates SoS from a regular system is the autonomy of the individual systems. Another study came from Wang et al. (2007) who clarified that SoSE is different than TSE where SE focuses on optimizing individual systems, while SoSE seeks to provide good enough solutions or near-optimization of networks of systems. They proposed a 5 layer-planning system to facilitate the SoSE process. Again, the field distinguished itself from traditional SE and seeking to provide frameworks to guide thinking and execution appreciative of those differences.

An important contribution came from Lane and Valerdi (2007b) where they analyzed 16 definitions and then determined a set of SoS characteristics that can be used to better estimate the cost (SoS cost model) of SoSE activities. After analyzing the 16 definitions they found the most predominant characteristics are emergent behavior, synergistic/higher level purpose, complex, interoperable systems, and mix of existing, new, or diverse systems. (p. 301). Kovacic et al. in (2007) conducted a case study to provide lessons from a project facilitated by the National Center for System of Systems Engineering (NCSOSE). The project identified the characteristics (wicked problems) associated with complex problems and how an agency can suffer from these wicked problems. As lessons learned, the authors showed the ramifications of not appreciating the nature of complex problems and the corresponding implications for addressing them.

To alleviate the issues of cost and schedule in SoS, Kasser, (2002) mentioned that the presence of fluid boundaries is one main characteristic of SoS. Bjelkemyr et al. (2009) provided a classification to the generic term SoS. The redundancy of higher level subsystems is used for their classification. The characteristics (evolutionary development, self-organization, emergence, network, and heterogeneity) are based on several definitions for SoS. Again, the evolution of the field suggests the need to differentiate from existing conceptualizations of systems and provide a different logical level for addressing SoS.

In 2008, Sauser et al. presented the paradoxical forces of the SoS characteristics which were adopted from Boardman and Sauser (2006). These paradoxes are examined in response to distinguishing systems from SoS. In the same vein, Gorod et al. (2008b) developed a "holarchical view" methodology to "identify the balance between the opposing forces" (p.5) (paradoxes) and therefore enable one to effectively engineer a SoS.

In terms of systems requirements, Hooks (2004) mentioned that the current requirements management process is insufficient for SoS. Thus, to better understand the requirements for SoS, it is essential to identify the scope of SoS. The scope involves the needs, goals, operational concepts, stakeholders, and objectives (Hooks, 2004).

In 2008, Keating et al. mentioned that in SoSE it is necessary to reframe our thinking (while at the same time continuing to appreciate the nature of requirements in SE) in regard to the role and nature of SoS requirements based on a distinctly different paradigm than SE. They proclaimed that SoS attributes (i.e. holism, complementarity, and fluid boundaries) preclude the success of the traditional requirements paradigm direct extension to SoS. To understand the context of SoS, it is necessary to look at the higher level SoS context rather than simply the local contexts of constituent systems. The primary reason is that the context of SoS emerges from the interaction of the constituent systems and therefore contains elements not relevant to the constituent's context (Shah et al. 2007).

Again, the theme of separation of the SoS field from traditional SE based formulations is apparent. However, the forms of that separation are as diverse as the authors exploring distinctions. While these distinctions are important, there are some commonalities in SoS characteristics. However, the evolution of the differences is not grounded in a conceptual or theoretical basis but rather finds a basis in the practical domain.

Third Category: Different Methodologies

The third emergent perspective in the development of SoS focuses on developing methodologies, approaches and tools. Soft system methodology (SSM) is a significant contribution that came from Checkland and Scholes (1990). Looking at multiple viewpoints (complementarity) and developing multiple conceptual models helps to inform appropriate decisions and actions undertaken to understand the problem situation. The idea of multiple models is to allow engagement in a high level of inquiry. Although not directly targeted at SoS, the extension of the SSM to SoS is certainly merited. In another study, Eisner et al. in (1991) and Eisner, (1994) developed a meta-systems framework (S2 Engineering for SoS) that was designed to help in formulating the approach to SoS. Three main categories constitute the framework

1. Integration engineering.
2. Integration management.
3. Transition engineering.

Since SE practices are not suitable to SoS, Hitchins (1992, 2003) proposed a methodology that emphasizes promoting variety to subsystems of the SoS (system of interest) to be able to deal with a changing environment. Checkland (1993) mentioned that a system "is perceived to be a mental model of something as opposed to a physical entity" [as cited in Cook, (2001), p. 3]. In a similar vein, Maier in (1994) argued that rational (traditional) methods are insufficient to analyze architectural problems that have inherently socio-technical components. Thus, he proposed a heuristic method that provides guidance to make decisions in such problems. In 1997, Kotov used the term large-scale concurrent complex systems to describe SoS. To lessen the complexity in modeling SoS, he developed hierarchical communicating structures based on data traffic and communication. In addition, *Nodes*, *Memory*, *Links* and *items* are the components that were used by Kotov to synthesize and model SoS.

From a military perspective, Manthorpe (1996) highlighted and analyzed the findings of a study conducted by the Naval Warfare Analysis Department. The thrust of the study was to gain a better understanding about the development and implementation of jointness (joint war fighting) among systems. This new structural and operational joint emphasis and interaction among systems (warfighting) have provided substantial benefits to battlefield awareness.

In a similar study, Pei (2002) pointed out the need to integrate complex systems. In order to achieve overall optimization of C4I2WS (Command, Control, Communications, Computers, Intelligence, Information Warfare, and Sensor) systems, a new program was established (System of Systems Integration). The main goal of the program was to provide overall development, interoperability, and solutions for C4I2WS integrated systems. This program was projected to be a benefit for the entire U.S. Army community. In the evolution of SoS, the particular contributions and dominance of the military perspective is considerable. One effect of this military perspective is the focus on practical applications, with little patience or emphasis on more theoretical or conceptual grounding for SoS methodologies. This is a constant theme in the evolutionary history of SoS – sacrifice of rigorous conceptual grounding for the immediate aims of improving practices related to development, deployment, and improvement of SoS.

Another significant contribution to the development of SoS came from Carlock and Fenton (2001). They addressed enterprise systems engineering (ESE) within the system of systems context. They identified three levels to effectively understand the development of large complex legacy systems (i.e. SoS). The ESE hierarchy processes is comprised of three main levels:

1. A top level that identifies the concepts and requirements needed for a SoS ESE, focused primarily on the context that meets user needs.
2. A middle level that navigates among system solutions provided from the top level and chooses the best solution (best investment) that is not necessarily the 'best' solution for individual systems, but rather optimal for the SoS.
3. The bottom level that implements the best systems solution obtained from the middle level, relying on the traditional systems engineering process.

These three levels are offered as an extension to classical SE processes. Of significance is the continuing theme of the SoS field desire to differentiate from traditional SE and the offering of conceptual approaches, rooted in practice but void of any philosophical or theoretical underpinnings.

Keating et al. (2003) contributed to the field of SoSE by scrutinizing existing systems-based methodologies and their attributes in relationship to the SoS problem domain. These attributes serve as a guideline to deal with and view SoS problems. In addition, Keating et al. (2003, 2008) made critical distinctions between SE and SoS. They developed a research model for SoS which consists of three levels, namely methodology, implementing processes, and techniques. The idea of the model is to facilitate the development of the SoS field. In the same manner, Keating et al. (2004) contributed to development of the field by developing a SoSE methodology with six phases and showed the appropriate applicability of the methodology to complex system problems. The development of methodology was consistent with the perspective of Checkland (1999) where it provides a guideline and perspective as an approach to deal with complex problems. The main purpose of the methodology is to help the practitioners to better take actions, make decisions, and develop consistent interpretations for SoS problems. The methodology was built based on:

1. Systems engineering,
2. System theory,
3. Systems philosophy,
4. Practice.

Noteworthy in this methodological development was the attempt to ground the methodology in systems theory.

In 2005, Keating provided a critique and challenge to the developing SoS field by offering a framework to better understand the source of divergence in the SoS field. The source of divergence was suggested as stemming from confusion, and failure to develop the field across five main developmental levels, including philosophical, axiomatic, methodological, method, and application dimensions. The author emphasized that to move the field forward would require a rigorous development across all the five levels and avoiding confusion generated by the thinking across different logical levels.

A very insightful development came from the Department of Defense (DoD) in 2006. DoD provided "16 technical and management processes to help sponsors, program managers, and chief engineers address the unique considerations for DoD SoS." [as cited in Valerdi, et al. (2007), p.12]. In the same year, Brooks and Sage (2006) made an observation regarding the integration of SoS. They clarified that the integration of SoS must include not only the technical processes but also the human aspects. They proposed a SoS approach to reduce the risk generated by the integration. The object of this approach was to define the risks early in the processes related to SoS.

In 2007b, Sahin et al. developed a framework for simulation of SoS. "They have presented an SoS architecture based on extensible markup language (XML) in order to wrap data coming from different systems in a common way." [as cited in Jamshidi, (2008), p. 6]. With another study, Sahin et al. (2007a) presented XML language to represent the communications without compatibility (hardware or software issues) among systems within SoS. To understand SoS practices, Valerdi et al. (2007) structured three different models namely a normative model, a descriptive model, and a prescriptive model. The first two models are concerned with the cultural standards and the behavior of the decision makers. The latter focuses on improving decisions from the former models. Sobieski in (2008) proposed an algorithm methodology for SoS to provide multi-optimization solutions. This set of works demonstrates the continuing struggles of SoS to focus on technical integration, but also appreciate concerns generated from the 'softer' aspects inherent in the SoS problem domain.

In a very interesting study, Gorod et al. (2008) developed a management framework to capture the academic and industrial perspectives to better understand and manage SoS. The framework is based on Boardman and Sauser (2006) SoS characterization (autonomy, belonging, connectivity, diversity, and emergence). The Fault Management, Configuration Management, Accounting Management, Performance Management, and Security Management (FCAPS) principles of information technology (IT) were used as a foundation for developing the SoS management framework. The framework is comprised of five main areas, namely Risk Management, Configuration Management, Business Management, Performance Management, and Policy management.

Along the same lines, Lane and Dahmann (2008) highlighted the findings of research conducted by the university of Southern California (USC) Center for Systems and Software Engineering (CSSE). The findings showed two main approaches that can be used to engineer and design SoS, namely, the SoSE model and the Incremental Commitment Model (ICM). The former is based on some SE practices (seven elements) that can be used in SoS. The latter deals with the risks endemic to the SoS life cycle. The purpose of ICM is to develop desirable system capabilities in a cost-effective manner. Again, the struggle of SoS to develop models and corresponding methodologies to support practice is evidenced in these developments.

Another study by Gorod et al. (2008c) used Boardman and Sauser's SoS characteristics to build a conceptual model to define and understand the role of flexibility in SoS. To enable dynamic flexibility in SoS, it is fundamental to design for:

1. Autonomy,
2. Decentralization,
3. Diversity,

4. Connectivity,
5. Unexpected behaviors.

In contrast, it was suggested that overwhelming flexibility will lead to chaos. Dagli and Ergin in (2008) emphasized that the applications of business and government should be integrated as a network to achieve desired goals. Thus, they developed a framework to articulate SoS. As evidenced by the development of the literature, SoS field development has shown a continuing emphasis on discovery of the practical applications of SoS. This is particularly the case with the military perspectives of SoS.

Rebovich (2008; 2009) made a distinction between classical systems engineering, SoS engineering, and enterprise systems engineering. He asserted that SoS represents a new mode of systems engineering and the focus is not on the single system but rather on the multiple constituent systems that comprise the SoS. For SoS, the technological integration aspect continues to be increasingly complex and therefore challenges our capabilities of understanding SoS from a technology perspective. Thus, he presented seven mega-processes tailored to SoS problems. The interrelationships among these seven mega-processes help engineers to view and frame SoS problems. Again, the 'practical' emphasis of the developing SoS field, with yet another articulation that provides (in this case processes) practitioners with assistance in dealing with SoS.

DiMario et al. (2009) contributed to the body of SoS by proposing a collaborative mechanism framework (coordination, cooperation, and collaboration). The framework suggested dealing with the new emergent behaviors as a result of collaborations and interactions between the constituent individual systems that form SoS. The SoS utility function is determined based on weighting the benefits versus cost for constituent systems. In the same year, Mansouri et al. (2009) studied the Maritime Transportation System (MTS) from a complex SoS perspective. The purpose of the study was to enhance resilience in Maritime Transportation SoS by applying a "Systemigrams" technique (storyboard).

In an interesting study, Adams and Keating (2011) proposed a SoSE methodology that is comprised of nine attributes and 7 main perspectives with 23 constituent elements. The applicability of the methodology depends heavily on framing and understanding the problem to be solved and the domain of the problem. The intent of the methodology is to provide a guide that helps practitioners in taking action, making decisions, and interpretations for SoS problems. The methodology is consistent with Checkland's (1993) perspective of a methodology. They clarified that system-based methodologies must provide guidance rather than detailed or prescriptive tools.

Following this study Keating (2011) provided an analysis of the second perspective, called *designing the unique methodology*, of the SoSE methodology (Adams and Keating, 2011). Designing the unique methodology relies on the (1) the nature of the SoS problem (2) context, and (3) the compatibility of the approach to the problem and context. This particular methodology for SoSE was different in that it was grounded in systems theory as the underlying theoretical basis. However, again the desire to provide approaches to facilitate the practice of SoS was evident. In the same year Jaradat and Katina (2011) proposed a terminology based on the SoS/E literature to lessen the confusion related to the use of SoSE terms.

Fourth Category: Principles and Axioms for SoS

The last emergent perspective focuses on articulating principles and axioms for SoS. In (1991) Rechtin identified some architectural design principles for complex systems known as heuristics (e.g. Policy Triage and Leverage at the Interfaces). However, in (1994) Maier refined these principles and showed how some of these principles can work as a guide for SoS (e.g. Policy Triage).

Jackson (1993) emphasized the need to have new approaches and methods to deal with growing SoS problems. Hayes, in (1988), argued that there is no clear distinction between different systems labeled as SoS. DeLaurentis et al. (2007) proposed a consortium to alleviate the ambiguities and provide remedies to SoS problems. The mission of the ICSOS (The International Consortium for System of Systems) "is to create a community of interest among science and engineering researchers and to foster proposals and solutions to advance the enhancement of SE to SoSE." (p.68)

Along the same vein, Gorod et al. (2007) contributed to the body of SoS knowledge by proposing the Systems of Systems Operational Management Matrix "best practices" based on the modified Fault, Configuration, Accounting, Performance, and Security (FCAPS) management principles to support and reduce the complexity for SoS. To effectively manage SoS, Sauser and Boardman (2008b) proposed four main principles that underline SoS thinking; legacy assessment, state-space solutioning, demystification and integration framework. Boxer et al. (2007) used the term "Double Challenge" to propose systems practices for building SoS with respect to collaboration.

Keating (2009) mentioned that to effectively deal with emergence (unanticipated events) in SoS requires full attention and appreciation of the philosophical, methodological, and axiomatic predispositions. "Divergence at the philosophic level can result in conflict with respect to how emergence is viewed and dealt within in a SoS endeavor." (p.176) Since the axiomatic foundations for SoS are still in the early stage of development, Keating et al. (2008, 2005) provided the application of ten systems concepts drawn from system theory (Clemson, 1984; Skytter, 2001) to the SoS problem domain. In addition, he presented three primary themes to tackle emergence. Similarly, Sheard and Mostashari (2009) presented some key principles for complex systems. They presented the key differences (i.e. integration, rapid evolutionary development, and unmanageability) between complex systems and SoS.

The researcher labeled this interval in the development of SoS as revolutionary. There was a significant generation of new concepts, approaches, and other developments aimed at enhancing the field and practical applications in SoS. Adams in (2011) showed how systems theory and systems thinking can help systems engineers frame and apply a holistic perspective with regard complex systems problems. He organized and grouped the different laws and principles of systems theory based on their utilities for SoS. This was a fundamental effort, and singular line of development for SoS, attempting to ground the field in an underlying systems theoretic foundation. However, the greatest mass of the field development for SoS has not shown the fortitude to engage either philosophic or theoretic grounding. Emphasis has been placed on developing pragmatic approaches, formulations, and guidance to perform SoS at higher levels.

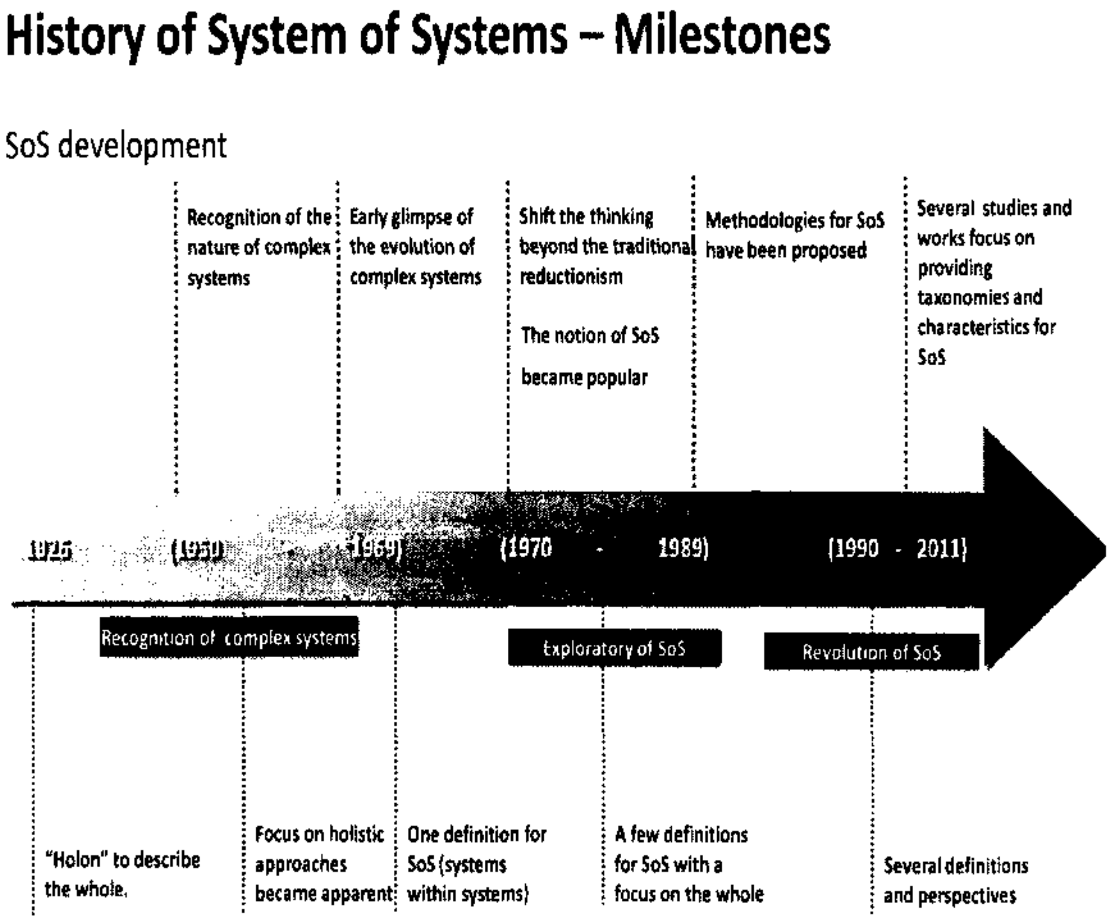
In review of the development of the SoS field, there is a noticeable absence of the deeper level grounding, and derivative understanding, from foundations in systems theory. In one respect this is not unexpected. Since there is a natural linkage to SE, SoS has similarly not favored theoretical and deeper conceptual development. On the contrary, emphasis in SoS field development has been targeted to practice enhancement. The concept of systems theory and systems thinking in this research focuses primarily on the principles, concepts, and laws that are necessary to understand complex problems as they exist at the individual level. While tools, methods, and methodologies for SoS will certainly increase in the future, grounding the field in a coherent set of underlying philosophical and theoretical foundations might provide an integration that would enhance viability (continued existence) and sustainability (long term propagation) of the field. Irrespective of field advances, there will be a necessity of individuals capable of executing in practice that which requires an implicit underlying grounding in systems thinking. Table 2.5 shows the main critical themes in this last interval.

Table 2.5: Main Themes for the 1990-2011 Interval

Critical themes for the third interval
• Revolution of the development of SoS with significant developments
• Multiple definitions, taxonomies, perspectives, foundational principles and methodologies proposed
• Symposiums, journal and conferences focusing on SoS flourished
• Achievement of some convergence regarding the characteristics of SoS

After analyzing over five hundred different resources, the researcher found there are some patterns endemic to the nature and development of SoS history. Although this articulation is not presented as absolute or definitive, it is offered as an effort to organize the evolution of the field. Figure 2.2 below shows the timeline for SoS history from (1926-2011) as well as the milestones for each interval. In Figure 2.2 the researcher attempts to provide a frame of reference for a field that is both diverse and fragmented.

Figure 2.2: Milestones of SoS (1926-2011)



As can be seen from Figure 2.2, the researcher has identified three major periods in the development of the SoS field. These include *Recognition* of SoS, *Exploration* of SoS and *Revolution* of SoS. From 1950-1969 there was recognition of the nature of complex systems, but there was also a lack of research pertinent to SoS. During this period, there was only one definition that described SoS. From 1970-1989 a few definitions were proposed, and the notion of SoS gained in popularity. The last interval (1990-2011) is considered the peak of SoS development (Figure 2.4). During this period the applications and formulations of SoS were extensive. However, also evident during this development was:

1. The relative absence of philosophical and theoretical grounding for the field;
2. An emphasis on development targeted almost exclusively to improving practices related to SoS;
3. A fragmentation and lack of coherence for the field.

This review of the literature for SoS/E serves as a major thrust for the current research. It provides a foundation for the problem domain that individuals are, and will continue, to be required to address.

HISTOGRAM ANALYSIS DISCUSSION

After an extensive review of the literature, the researcher found that three main intervals can trace the nature and development of SoS (Figure 2.2 & 2.4). In the last interval (1990-2011) the researcher identified common themes that appear to mark the development of SoS through writings and studies focused on:

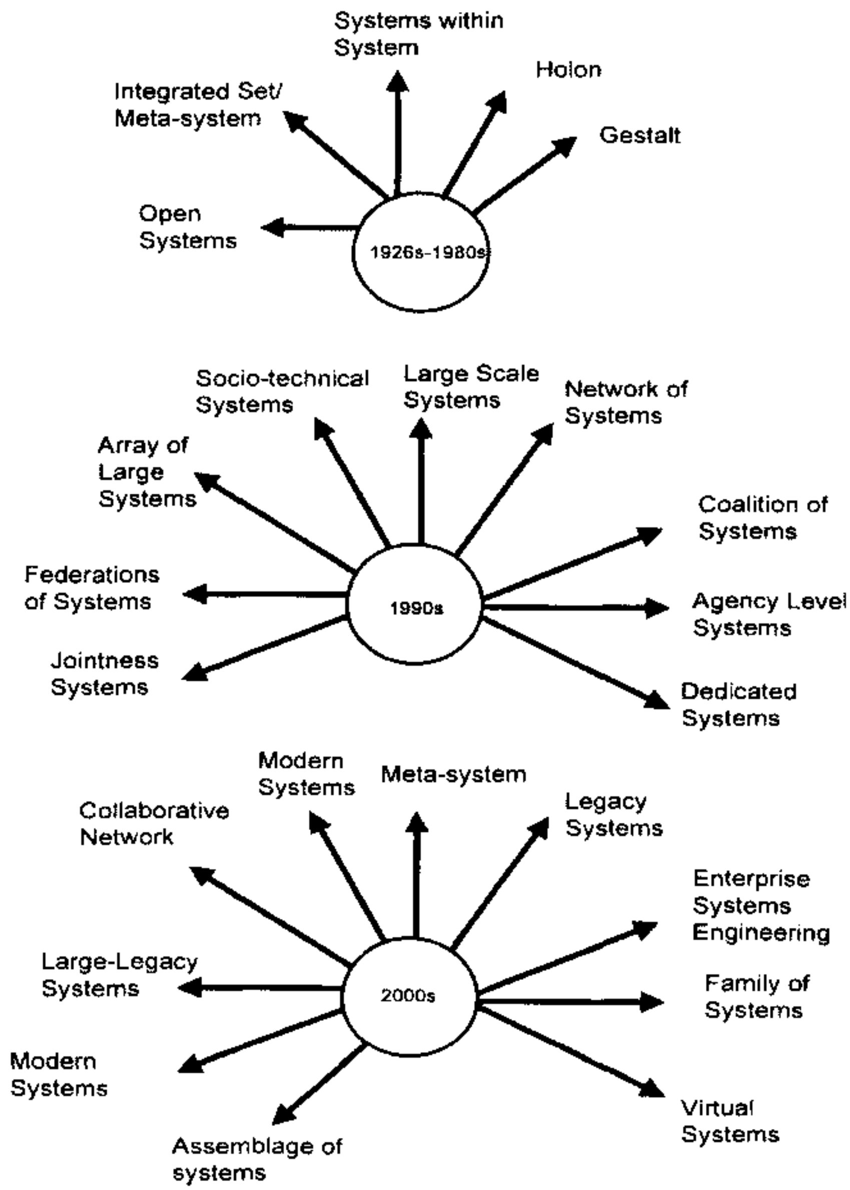
- Providing definitions for complex systems (SoS) with a focus on treating a system as a whole.
- Identifying characteristics for SoS.

- Contributing to the field targeted to developing tools, frameworks and methodologies targeted to enhance practice.
- Distinguishing complex systems from traditional systems engineering.
- Limiting identification of principles and axioms for SoS.
- Palpable absence of philosophical and theoretical development of the field.

Although the field of SoS has evolved over the three intervals, it is important to mention again that Ludwig Von Bertalanffy (LVB) is considered the father of general system theory, but his work has somehow not figured prominently in the development of the SoS field. Von Bertalanffy's, coupled with subsequent development of the systems related fields (e.g. systems theory, cybernetics) have eluded the SoS field, as well as the SE field. This is unfortunate because this natural fit might provide the philosophical and theoretical grounding that has been identified as largely absent from the SoS field development. Von Bertalanffy provided a universal language and laws that crossed multiple fields with a much more universal applicability. The universal language and laws might provide an effective foundation of complex system domains. System theory and systems thinking are key to understanding complex problem domains and their inclusion might be a significant contribution to future integration and development of the field.

Stemming from a thorough review of these intervals (1950-2011) we found that several researchers use different terminologies to describe SoS. Figure 2.3 below depicts these terms and concepts in chronological order.

Figure 2.3: Different Terminologies for SoS (1950s-2011)



From these terms and definitions, along with attributes in the literature, the researcher draws some conclusions with respect to the current state of complex systems/SoS. First, there is some generalized agreement on the characteristics which are present in complex systems/SoS (e.g. operational independence, managerial independence, geographical separation, emergent behavior and evolutionary development (Sage and Cuppan, 2001; Maier, 1998; Keating, 2011). Second, the literature is fragmented. This is evident from the lack of consensus in terms, approaches, or accepted fundamentals of the field. Keating et al.,(2003, p.2) state that "although continued fragmentation will serve to increase dialogue, at some point the dialogue will need to provide convergence around accepted perspectives of the phenomena associated with SoSE." Third, systems engineering, at least in the preponderance of thinking reflected in the literature, is a primary foundation of SoS. Systems theory, systems thinking, and advances in related fields such as cybernetics have not been part of the mainstream development of the emerging field of complex systems/SoS. Table 2.6 below shows the explanation for each of the aforementioned terminologies.

Table 2.6: SoS Terminologies (1926-2011)

Term	Explanation	Author
Holon	"Holon" describes the whole and parts of a system	(Smuts, 1926)
Gestalt	In his complexity hierarchy level 9 represents SoS	(Boulding, 1956;keating et al. 2003)
Systems within systems	Cities within cities	(Berry, 1964)
Integrated set	the relationships between the elements are difficult to trace	(Ackoff, 1971)
Meta-system	Integration of systems	(Beer,1972)
Open systems	SoS are pluralistic in nature	(Jackson and Keys, 1984)

Table 2.6: Continued

Social-technical systems	Systems that involve both technical and social components	(Mitroff and Linstone, 1993; Maier, 2005; McCarter and White, 2008; Clark, 2009; Delaurentis et al.2006)
Network of systems (array)	Net of systems to achieve specific purpose	(Shenhar, 1994)
Coalition of system	C2 systems in military	(Owens, 1996)
Jointness	Link of systems	(Manthorpe, 1996)
Large-scale systems	Large concurrent complex systems	(Kotov, 1997)
Federations of systems (decentralized power)	Group of systems connected together to produce new behavior	(Krygiel et al. 1999; Sage and Cuppan, 2001)
Dedicated systems	Large complex systems consist of large complex subsystems	(Allison and Cook, 1998)
Agency level systems	Multi-extension systems levels of SE	(Carlock et al. 1999)
Virtual systems	Integration of systems (military) to accomplish emergent need	(Cook, 2001)
Modern systems	Not-monolithic systems	(Sage and Cuppan, 2001; Maier, 1996)
Legacy systems	Large complex SoS (Enterprise systems engineering)	(Carlock and Fenton, 2001)
Assemblage of systems	Collaborative network systems	(Maier, 2005)
Large-scale systems	Integration of multiple systems and their subsystems	(Northrop et al. 2006)
Family of system	Integrated systems	Clark, 2009

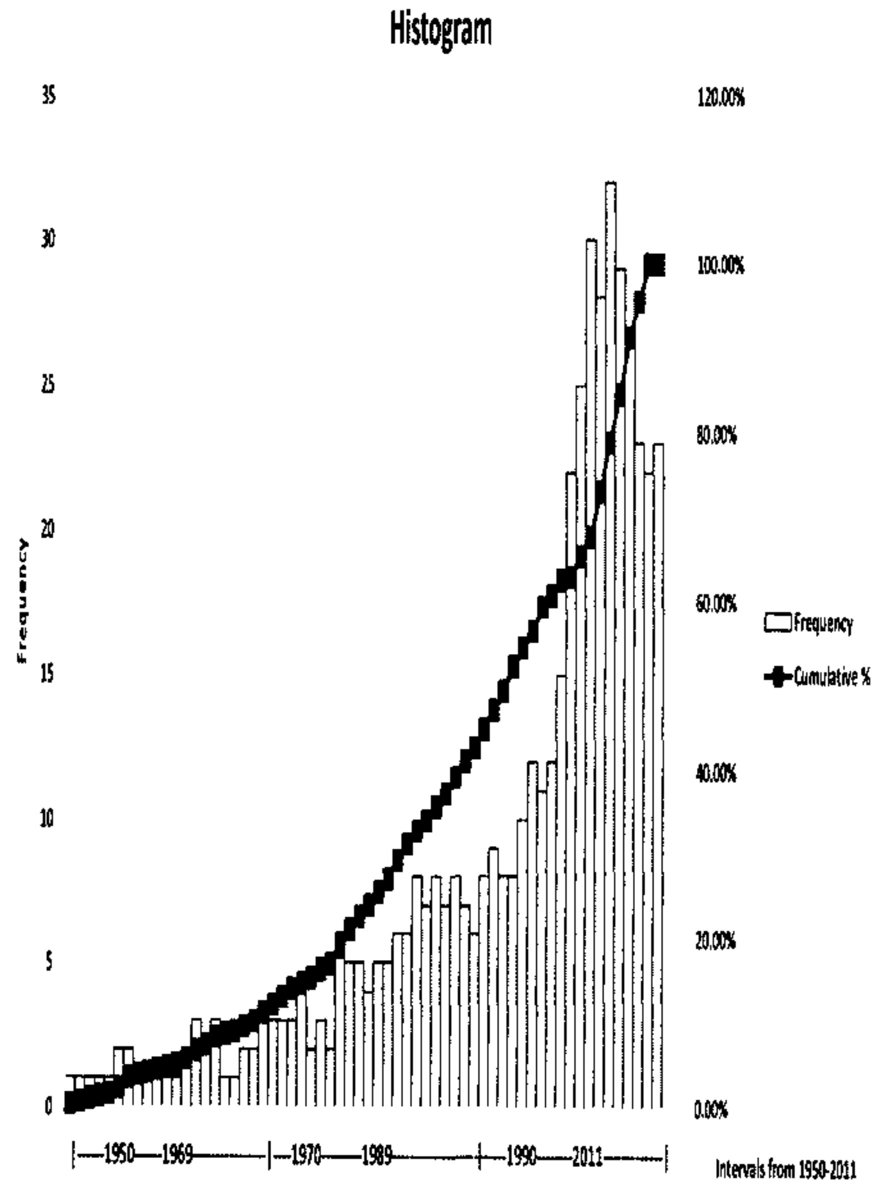
While this listing is certainly not complete, it demonstrates that the breadth of SoS and related thinking has been around in multidisciplinary forms for a significant period.

The histogram below (Figure 2.4) depicts the shape of the distribution for development of complex systems/ SoS as evidenced by the publication activity during the periods. As mentioned earlier, the researcher used several criteria to be included in the analysis. These criteria are

1. Definitions for complex systems/SoS,
2. Characteristics for complex systems,
3. Methodologies for complex systems/SoS,
4. Principles and axioms for complex systems/SoS,

There are three interval classifications (1950-1969), (1970-1989), and (1990-2011) (horizontal axes) as shown in Figure 2.4.

Figure 2.4: Histogram Analysis for SoS



The finding of the histogram analysis shows that the last interval (1990-2011), identified in Figure 2.2 as *Revolution of SoS*, contains the highest frequency as well as the highest cumulative values. This means that this interval is considered to be the peak of SoS development. This interval has witnessed a rapid development in the body of SoS. Studies, works, presentations, conferences, symposiums, and journals with respect to SoS abound in publications such as the IJSSE journal. In 1990, The International Council on Systems Engineering (INCOSE) organization was founded to deal with complex problems, and in 2002 the National Centers for System of Systems Engineering (NCSOSE) was formally established to focus on SoS problems. Other centers such as the Southern California for System and Software Engineering (CSSE) and the School of Engineering at Purdue were established for the same purpose. In addition, the end of this period shows a decline in activity related to SoS. What this portends for the future of the SoS field is questionable, but the palpable reduction cannot be denied.

The 1970-1989 interval, identified in Figure 2.2 as *Exploratory of SoS*, showed an interesting movement toward the development of SoS; the shape fluctuates but the end of this interval showed more contributions to the body of SoS. In this interval, the notion of SoS became popular with a focus on the "whole". Appreciating that resolutions and understanding of SoS problems would require both 'hard' systems (technology) as well as 'soft' systems (human/social, organizational/managerial, and political/policy) considerations. The first interval (1950-1969), identified in Figure 2.2 as *Recognition of SoS*, showed only recognition to the nature of SoS with a few definitions. In fact, some of these did not directly address SoS but only offered initial, and sometimes tangential, implications for SoS. The most common theme in this interval is that there was a general agreement on moving beyond the traditional view of systems engineering to more holistic approaches. The flow of the distribution makes sense and it is to be expected because the field of SoS is relatively new. It is important to mention that the histogram does not display individual data (year by year) but allows the reader to see the shape of the distribution to observe the general form of the development of the field as the gestalt of works being produced.

THEMES AND CRITIQUE OF THE LITERATURE

Traditional systems engineering (TSE) has proven successful in providing tools and methods for systems to cope with problems that have a direct cause-effect relationship, but these methods and tools have not enjoyed the same level of success in socio-technical problems. Keating (2009), and Blanchard and Fabrycky (1998) emphasized that the traditional systems engineering approaches are successful in dealing with purely technical problems with clear delineation of boundaries.

The potential availability of tools that might be applicable to the socio-technical problems systems is vast (Keating et al. 2008; Chattopadhyay and Rhodes, 2008; Sindiy, et al. 2007). However, these methods and tools have been primarily developed for, or borrowed from, other fields. They have not been purposefully developed or deployed for large scale complex problems. Thus, the applicability of the traditional systems engineering tools and methods as a simple extrapolation to the SoS problem domain must be met with a degree of skepticism. The critical point here is not to criticize the existing tools available for use in the complex problem domain. Instead, the major issue is that these tools have not been purposefully designed to deal with socio-technical problems. Thus, the complex problem domain is ripe to develop new tools, or modify existing tools, such that appropriateness to socio-technical problems will be better supported.

The limitation in the application of traditional SE and the lack of understanding and consideration of elaborative interactions and interdependencies that exist among systems of systems, hinder their application in SoS-based approaches. In fact, traditional systems engineering strategies are slow to respond to rapidly changing technologies and other challenges faced in twenty-first century systems (Azani and Khorramshahgol, 2005). Stemming from an exhaustive review of the literature, Tables 2.7 and 2.8 show some of the themes and critiques in the complex systems/SoS literature.

Table 2.7: Themes of the Literature

Author	Synthesis of General Theme
DeLaurentis, (2005); Keating et al. (2003); Bonaceto and Burns, (2006); Sega and Cuppan, (2001) and Kotov, (1997)	There is no one accepted definition and articulation for SoS
Sega and Cuppan, (2001); Dahmann et al. (2005); DeLaurentis and Callaway, (2004) and Shenhar, (1994)	SoS is useful in dealing with multidisciplinary problem across a variety of application
Keating et al. (2008); Azani and Khorramshahgol, (2005); Keating, (2009); Maier, (1998); DiMario et al. (2008); shenhar, (1994); Eisner et al. (1991); Blanchard and Fabrycky, (1998)	SoS is established to effectively address the complex problem where traditional system engineering is no longer able to deal with SoS problems
Keating et al. (2003); Sousa-Poza et al. (2008); Keating, (2009)	Even with the diversity in SoS perspectives, there is some convergence associated with SoS articulation
Ring and Madni, (2005); Keating et al. (2004); Manthorpe, (1996)	There is no specific methodology for SoS. It depends on the system's purpose and the surrounding context

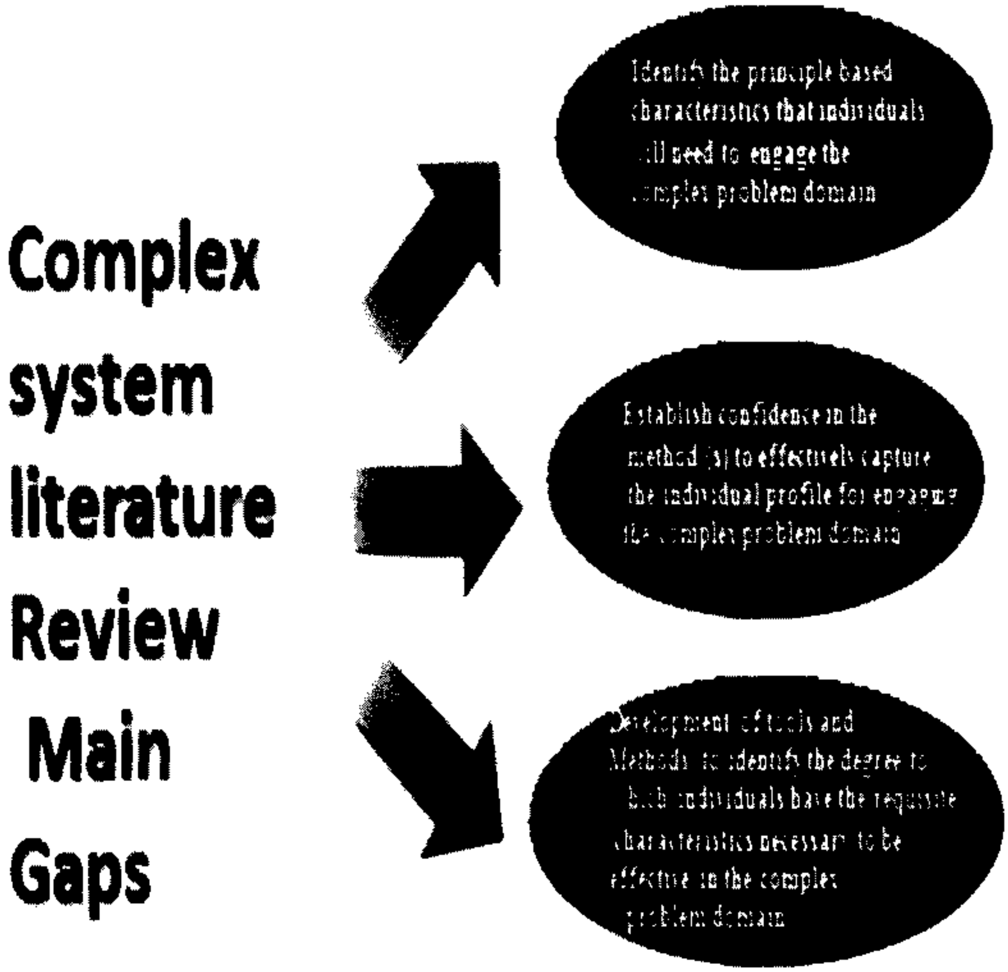
Table 2.8: Critique of the Literature

Author	Critique of the literature
Keating et al. (2003); Mansfield, (2005); Sauser and Boardman, (2008b); Adams and Keating, (2011); Boardman and Sauser, (2008)	Incomplete developing of perspectives and articulations of SoS and Lack of philosophical, methodological, axiological and axiomatic components
Johnson, (2002); DeLaurentis, (2005); Maier, (1998); Boardman and Sauser, (2006); Jackson and Keys, (1984); Kotov, (1997); Keating, (2009); Sega and Cuppan, (2001); Jamshidi, (2008); Maier, (1994); Dagli and Ergin, (2008)	Regardless of the numerous tools and techniques that can be applied in SoS, these tools are not purposefully designed to deal with complex problems domains. These tools and techniques are adopted from other fields
Keating et al. (2003); Dahmann et al. (2005); Ring and Madni, (2005); Kotov, (1997); Maier, (1998); Delaurentis et al. (2007); Baldwin and Sauser, (2009); Keating, (2005)	The theoretical work is not well established (need inquiry)
Ryschkewitsch et al. (2009); Derro and William, (2009); Frank, (2006); Gorod et al. (2008); Chen and Clothier, (2003); Maier, (1998); Adams, (2011); Keating et al. (2004); Keating, (2009); Dahmann et al. (2005)	Even there are some studies that provide characteristics for system engineers, but there is no similar capture of characteristics for system engineers to engage the system of systems problem domain

MAIN GAPS IN THE LITERATURE

From the survey of literature, there is a significant gap that has not been addressed. From the current state of the complex systems literature, there are three important points that can be synthesized as a significant gap that might be addressed through rigorous scholarly research. First, the current focus complex systems has not addressed issues related to whether or not an individual has the disposition to effectively engage the complex problem domain. This necessity to match knowledge, skills, and abilities of a SoS team has been a subject of discussion in the SoSE methodology posed by Adams and Keating (2011). Second, while there have been some rudimentary efforts to identify the characteristics that are necessary for systems engineers to be successful (Frampton et al. 2005; Di Carlo et al. 2006; Frank, 2006), there is nothing that has been engaged to identify the characteristics necessary for individuals to be effective in complex problems endeavors. Third, even if the characteristics necessary for success in a system of systems problem domain existed, the tool(s) necessary to generate the degree to which an individual might possess these characteristics does not exist. There is much to be gained through rigorous scholarly development of foundations and the development of tools to examine the propensity for individuals to engage in the level of systems-based thinking necessary to effectively engage the holistic problem domain. Therefore, Figure 2.5 illustrates the gap related to understanding the individual propensity for engaging systems thinking. The current literature has not shown a rigorous research focus to determine the individual capacity for systems thinking.

Figure 2.5: Main Gaps



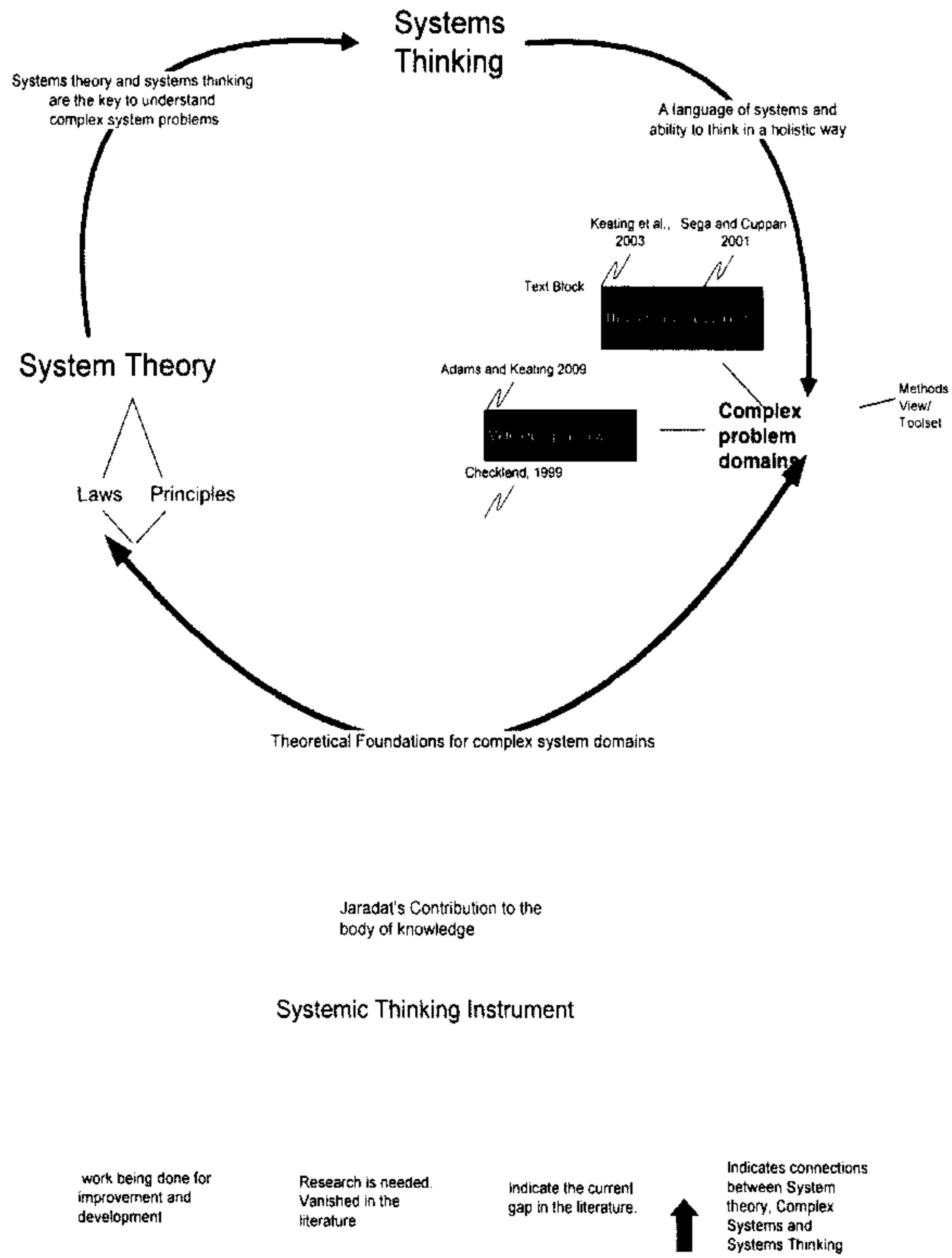
Although there are other gaps in the literature, the focus on determining the individual capacity to possess the characteristics necessary to engage complex problem domain is compelling as a significant contribution. As mentioned above and throughout the chapter, the current tools are either adopted or extrapolated from other fields such as systems engineering. Therefore, there is an essential need to build a tool "purposefully" designed to understand the degree to which an individual has the systems based capacity to effectively deal with complex problem domains.

Chapter III explains the phases of rigorously developing such an instrument to support establishing a systemic profile at the individual level. The literature for complex systems fails to form a set of characteristics that individuals should possess to deal with the complex problem domains. Therefore, there is a need to engage research that can

1. Identify systems-based characteristics essential to the complex problem domain and
2. Establish mechanisms to identify the degree to which those characteristics are present for an individual.

Figure 2.6 below shows the map of the literature review for this research and positions the research as an original contribution to the field.

Figure 2.6: Literature Review Map



SYSTEMS THINKING

Systems thinking is the third thread in the development of the literature (Figure 2.1) The intent of this section is to show the specific role systems thinking plays to understand complex system problems.

SYSTEMS THINKING DEFINITIONS

Systems thinking is the thought process which develops the ability to think and speak in a new holistic language (Checkland, 1993). In his definition of systems thinking Checkland emphasized the concept of wholeness to understand complex problems. Senge (1990) mentioned that "systems thinking is a conceptual framework, a body of knowledge and tools that has been developed over the past fifty years, to make the full patterns clearer, and to help us see how to change them effectively." (P.7) Adams and Keating (2011,p.11) stipulated that understanding the principles of system theory, "in conjunction with the thought process developed in systems thinking" is a vital and key step toward understanding SoS endeavors. The principle of holism is the foundation of systems thinking. Table 2.9 below provides some of the current perspectives concerning systems thinking.

Table 2.9: Systems Thinking Perspectives

Author	Perspectives
Checkland (1999, p. 318)	"An epistemology which, when applied to human activity is based upon the four basic ideas: emergence, hierarchy, communication, and control as haracteristics of systems. When applied to nature or designed systems the crucial characteristic in the emergent properties of the whole"
Senge (1990, p. 7)	"systems thinking is a conceptual framework, a body of knowledge and tools that has been developed over the past fifty years, to make the full patterns clearer, and to help us see how to change them effectively"
Flood and Carson, (1993, p,4)	"A framework of thought that helps us to deal with complex things in a holistic way"
http://opbf.org/open-plant-reeding/glossary/so-sz	"A system cannot be understood by an analysis of its parts. Systems thinking concerns the organization of those parts, as a single system, and the emergent properties that emanate from that organization."

Table 2.9 shows that there is no one accepted perspective or unique definition of systems thinking. There are many perspectives concerning how we think about the complex system-based world.

HARD AND SOFT SYSTEMS THINKING

According to Checkland (1999) there are two forms of systems thinking: hard and soft thinking. Hard thinking is appropriate in complex problems that have technical components, while soft thinking is appropriate in ill-defined situations. Table 2.10 below shows some of attributes for each systems thinking type. The researcher combined the work of Jackson (2003), Waring (1996), and (keating et al. 2010) to construct the table.

Table 2.10: Hard and Soft Thinking

Attribute	**Hard Thinking**	**Soft Thinking**
Understand the problem	Break the problem into parts	Look at the whole system level
Objective	One best solution	Multiple good enough solutions
Work Environment	Stable with minimal change	Rapid shifting changes
Perspective	Alignment of perspectives	Multiple divergent perspectives
Modeling	Exact relationship	Non quantitative in nature

SYSTEMS THINKING AND COMPLEX PROBLEM DOMAIN

The concept the researcher used for systems thinking in this research is focused on capturing the systems thinking characteristics that are necessary for individuals to engage in higher level (holistic) thinking about complex problems and how they approach these problems. Systems thinking is recognized as a main tenet to think in a holistic language and provide a foundation for essential capabilities to more effectively navigating a complex problem domain. As such, "systems thinking is instructive in helping to explain and understand why there will never be a universal solution to the issues that complexity brings to human endeavors." [Keating et al. (2010), p. 250] Therefore, for truly complex problems, systems thinking can transcend technical knowledge in developing robust 'holistic' solutions.

Systems thinking, based in system theory principles and laws, plays a vital role in understanding and dealing with complex problem domains. The concept underlying the proposed *systems thinking characteristics instrument* is determination of systems thinking of individuals who will be required to 'holistically' appreciate and operate in the complex problem domain ranging from industry to military contexts.

Systems thinking is taken as a foundation necessary for individuals to effectively engage in thinking, making decisions, and constructing coherent interpretations concerning complex problems, and how they might be effectively approached. Success in these complex problem domains also depends on the degree to which one thinks in a holistic language that enables effective systems thinking, and subsequent engagement, of complex system problems. Further, systems thinking is suggested as an essential capability necessary for individuals to effectively deal with the complex problems across several domains. While systems thinking is not posed as a universal solution, it does offer a more robust level of thinking for dealing with complexity as evidenced by the literature for systems thinking. However, there is a recognized absence of rigorous research based instruments to identify the level of (capacity) individuals for engaging systems thinking. This is in spite of widespread acknowledgement in the literature extoling the virtues of systems thinking and tool/methods (e.g. system dynamics) to practice and develop systems thinking based products.

SUMMARY

This chapter has shown the main threads and schema in the development of the literature in this research namely system theory, complex systems/SoS. and systems thinking. This chapter has provided the current themes and critique in the literature. It also highlighted the main gaps in which positioned this research as a unique contribution to the complex problem domains. This chapter has provided a histogram analysis for SoS history. The central idea of this histogram is to trace the origin of the history of SoS by analyzing a sample of over 500+ different sources germane to SoS. Even though this is a sample, it offers a glimpse into the historical development of the SoS field and invites an ongoing dialog concerning the past and its implications for the future developmental directions of the field. The histogram presented in this chapter provides a better understanding and visualization of the evolution of the body of SoS. This is important to the current research in establishing the nature of the complex (system of) systems problem domain that characterizes that faced by modern practitioners. This chapter is considered the foundation for Chapter III which will provide a detailed description of the research design, methodology, and the development of the new systems thinking instrument.

CHAPTER III

RESEARCH DESIGN AND METHODS

This chapter provides a detailed discussion of the approach the researcher followed to construct a rigorous research design along with the rationale for the selection of a mixed research design. In this chapter, the researcher also explains how he derived the set of systems thinking characteristics individuals need to engage complex problem domains, provides the phases of building the new systems thinking instrument, and discusses the systems thinking profiles which are the outcome of the instrument application.

Research design is a blueprint to guide a research process starting with the purpose of the study and ending with the final outcomes. It is a comprehensive planning process used to collect and analyze information in order to increase our understanding of a given topic. At a general level, the research process consists of three steps: posing a question, collecting data to answer the question, and presenting an answer to the question. The primary purpose of a research design is to provide a solid foundation so that a robust research approach can be developed. To obtain a rigorous research design, the researcher adopted Babbie's (1999) and Creswell's (2008) philosophy in defining the steps of the research design process. The following steps were used to develop a rigorous research design.

RESEARCH DESIGN APPROACH

In this section, the approach to development of the design is established. This is essential for understanding the development of the approach, consistent with mounting a response to the research questions undertaken for the research.

- ***Define the purpose of the research***

This step was accomplished in Chapter I by identifying the main underlying purpose of the research and derivative research questions. The purpose of this research is to develop and deploy a systems thinking instrument to capture the state of systems thinking at the individual level to deal with complex problem domains.

- ***Conceptualize the research terms***

After articulating the purpose of the research and research questions, the researcher next identified the particular terms that provide a foundation essential to placing the research in context and clarifying critical language. This step was accomplished in Chapters I and II by defining the exact meaning of the concepts and terms critical to proper understanding of the research.

- ***Choose the research method and methodology***

Chapter III explores the development of a systems thinking instrument used to collect data and describe the research methodology. An in-depth discussion is provided in the sections to follow. In this step the researcher also specified the research procedures to develop the systems thinking instrument and showed how the data was collected, analyzed, and used to inform development of the instrument.

- ***Select the population and the sample of the research***

Next, the researcher described the population as well as the sample of the study. The decisions about population and sampling are related to decisions about the research method for data collection to be used are elaborated upon. The chapter discusses this step in depth.

- ***Observe and prepare the dataset***

In this step, the researcher prepared the extensive dataset collected for analysis. Factor analysis (exploratory factor analysis) and Monte Carlo simulation were used to analyze the dataset. The design for this analysis is included in Chapter III and the results are reported in Chapter IV.

- ***Analyze and interpret the dataset***

In the final step, the researcher interpreted the dataset for the purpose of drawing conclusions and then clarified the applications of the research across theoretical, methodological, and practical dimensions. Further, the researcher provided recommendations for future research based on the interpretation of results from the study.

TYPE OF RESEARCH DESIGN

There are three main types of research design: quantitative research, qualitative research and mixed methods (Creswell, 2008). "Quantitative and qualitative designs should not be viewed as polar opposite; instead, they present different ends on a continuum." [Newman and Benz, as cited in Creswell, (2008), p. 3] More recently, researchers have developed a new research design called mixed method research to answer unobtainable questions (Carey, 1993). This new design, positioned in the middle on Newman and Benz's continuum, is the most suitable type of research design for this study. The researcher used a mixed methods design because it has characteristics from quantitative as well as qualitative designs. The rationale for selection of the mixed method design is

1. To employ the quantitative and qualitative approaches and include sequential and concurrent mixed methods,
2. To achieve the research purpose as mentioned in Chapter I, and most importantly,
3. To answer the main questions of the research.

As presented in Chapter I, the first question is:

What systems thinking characteristics are needed for individuals to effectively deal with the complex problem domain?

To answer this question the researcher used a qualitative approach, grounded theory coding, to derive the set of systems thinking characteristics from the literature. Based on those characteristics, a system thinking survey instrument was developed to examine the existence of the characteristics at the individual level. The following sections provide a detailed discussion of the construction of the systems thinking characteristics for use in the systems thinking instrument.

The second question and the alternative hypothesis of the research are:

How can systemic thinking characteristics be examined to classify an individual's level of systemic thinking to deal with the complex problem domain?

H_1: *there is a statistically significant relationship between the proposed systems thinking characteristics (Sc) and the state of systemic thinking at the individual level that would indicate predisposition for engaging in the complex problem domain.*

To answer the second question, the researcher used a quantitative approach to analyze the dataset and to validate the utility of the new systems thinking instrument. Mixed method design strengthened the research outcomes and helped to achieve the research purpose and goals. In fact, neither the qualitative approach nor the quantitative approach alone would have been able to answer the two main questions of the research and make a decision with respect to accepting or rejecting the hypothesis. This is another reason why the researcher used mixed methods design. Further, to reject or accept the null hypothesis, the researcher conducted factor analysis (quantitative approach). The next section explores the detailed research design phases from which the systems thinking characteristics (7-Sc) emerged.

RESEARCH DESIGN PHASES

To achieve the purpose of the research and to answer the research questions, three phases were proposed to conduct this research. Figure 3.1 provides an overview of the three phases.

Phase I

The focus of this research phase was to identify the set of systems thinking characteristics that are essential to engage complex problem domains. As discussed throughout Chapter II, there are no specific tools, methods or techniques purposefully designed to establish the (systems thinking) capacity of individuals to deal with complex problem domains. The potentially related methods (e.g. stakeholder analysis) are either adopted or extrapolated from other fields. In this phase the systems thinking characteristics were derived from the literature using grounded theory coding, executed using Nvivo (QRS International, version 10, 2014) to help organize the huge dataset.

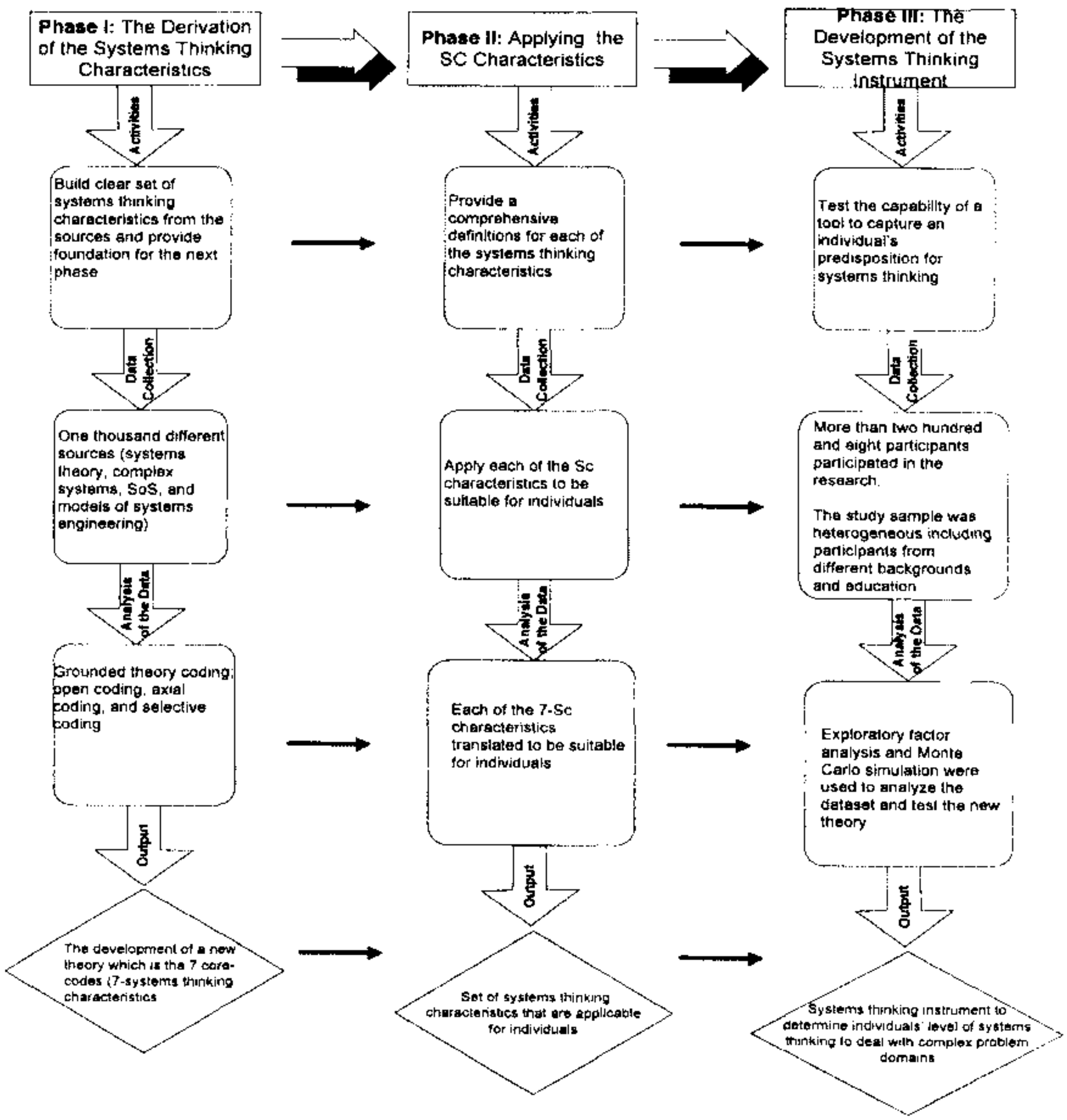
Phase II

This phase applied the set of systems thinking characteristics identified from the literature for individuals. In this phase the systems thinking characteristics were applied to fit individuals, and a comprehensive definition was developed for each systems thinking characteristic.

Phase III

This phase of research tested the capability of the instrument to capture an individual's predisposition for systems thinking. This was achieved by developing a systems thinking survey instrument that captures an individual's predisposition for systems thinking through interaction with a scenario and delivered via web-based survey software. While technology has been increasing exponentially, the corresponding methods to harness those technological advances and the problems they have spawned are lagging. To date, in organizational systems spanning healthcare, nuclear power, transportation, education, etc. there is a broad collection of methods, techniques, technologies, and tools that can be used in dealing with problems. However, these methods have not always been purposefully developed nor properly deployed to deal with the emerging multidisciplinary problem domains characteristic of the 21st century, nor have they been purposefully coupled with people based on an individual's proclivity and capacity to engage in a level of systems thinking commensurate with that (implicitly) required of a method. Therefore, in this phase, the researcher constructed a new systems thinking instrument that is purposefully designed to determine individual capacity to deal with complex problem domains. The systems thinking instrument consists of 39 binary questions and a scenario that describes a generalized complex system problem.

Figure 3.1: Detailed Research Design Phases



All three research phases described above entailed reasoning. "Inductive reasoning "...begins with statements of particulars and ends in a general statement" [Lee and Baskerville, (2003), p. 224] while deductive reasoning, which is usually used in quantitative research, starts from general statements and moves to more specific statements.

An inductive approach (Rips 1990) was used for Phases I and II. Phase III was accomplished by developing an implementation instrument and performing a preliminary testing of the instrument. The researcher used an inductive research approach, grounded theory coding, to derive the systems thinking characteristics needed to engage in complex problem domains. The qualitative inductive approach was used to answer the first question in the research. The data for the inductive approach came from an extensive review of the literature. The boundary of the literature used to derive the systems thinking characteristics consists of three main divisions: system theory, complex systems/SoS and systems thinking.

Specialized software, Nvivo (QRS International version 10, 2014) was used to navigate and manage the huge amount of qualitative data in the research. After deriving the set of systems thinking characteristics, a scenario was developed to allow participants to engage the instrument for measurement of individual capacity for systems thinking.

Before discussing the research design phases (I, II, and III) that produced the set of systems thinking characteristics necessary for individuals to deal with complex problem domains, the following two sections provide an introduction to the structure of grounded theory coding and the rationale for selecting Nvivo software.

GROUNDED THEORY CODING (INDUCTIVE APPROACH)

This research used grounded theory coding to derive the set of systems thinking characteristics. This section describes grounded theory coding and in particular the role that grounded theory played for the research design.

BRIEF HISTORY OF GROUNDED THEORY CODING (GTC)

Glaser and Strauss (1967) founded grounded theory coding during their successful research regarding dying hospital patients. They invented a method that enables researchers to obtain empirical data through coding procedures. Even though grounded theory coding is qualitative in nature, it integrates the "strengths inherit in quantitative methods with qualitative approaches" [Walker and Myrick, (2006), p. 548]. Grounded theory coding (GTC) challenges the deductive reasoning in research regarding the development of a theory. Glaser and Strauss clarified that with GTC the researcher starts by gathering specific data and then develops a valid theory (from specific to general) (Dey, 1999). They argued that the theory will be validated because it is generated directly from the specific dataset. Glaser and Strauss (1967) have identified the following criteria to support effective grounded theory coding:

1. The coding procedure should stick closely to the data under study.
2. The initial coding should be flexible and modifiable over time. Put another way, in the initial (open) coding a researcher should be open to include any new patterns that might occur over time (Charmaz, 2006).

Glaser and Strauss's method has been used widely by researchers, students and others. However, in 1978 and 1987 they provided two different methodologies regarding their grounded theory coding. The appropriateness for selection of one of the two versions of these methodologies is based primarily on the nature of the research, the researcher's role, and the dataset (Walker and Myrick, 2006). The originators' versions of grounded theory coding are imbued by their epistemological and ontological assumptions (Charmaz, 2006). It is imperative to mention that even though there are two current versions, "both of them used coding, the constant comparison, questions, theoretical sampling, and memos in the process of generating theory." [Walker and Myrick, (2006), p.550] Further, both of the versions start with particular data and end with a developed theory that is derived from the specific data through coding phases. Even though there are some differences between the versions, there are many similarities as well. Encompassing all these similarities and differences is beyond the scope of the chapter. However, what is germane to the current research is which version the researcher used to develop his theory, the set of systems thinking characteristics, and why.

Glaser's version (Glaser, 1992) of grounded theory consists of two main coding stages, namely, substantive and theoretical coding. The substantive stage consists of open and selective coding. In contrast, Strauss's version (Strauss and Corbin, 1990) of grounded theory is comprised of three main "coding" phases: open coding, axial coding, and selective coding. Charmaz (2006) mentioned that the initial coding in grounded theory involves "naming each word, line, or segment of the data set" (p. 46). Axial coding, the second stage in coding, plays an important role in selecting the most frequent-significant initial codes through a large amount of data. The axial coding provides analytic themes of the data. Selective coding is the last procedure in the grounded theory coding. In this code the researcher selects the most coded data and generates a theory.

In this research, the researcher used Strauss's version as discussed in Strauss and Corbin (1990) to derive the set of systems thinking characteristics that embrace the data; however, the researcher used the constant analysis technique from Glaser's version.

Following Strauss and Corbin (1990), the researcher used three main procedures in conducting grounded theory coding:

1. Open coding, which is a procedure to link chunks of data together, was performed. In this phase the researcher examined the sources of data that support engaging in systems thinking (complex systems, systems engineering models, systems thinking, and system theory) and coded the data until a particular concept of "systems thinking characteristics" was derived.
2. Upon completion of open coding, axial coding, which served as a filtering step, was performed. Using axial coding the researcher identified the reasons for having particular codes.
3. Selective coding, which involves building hierarchical grouping of codes, was performed to organize the codes generated in previous coding. In this phase the researcher chose the core-codes (most coded codes) that formed the theoretical framework of the research.

The rationale for selecting the Strauss version (Strauss and Corbin, 1990) of grounded theory coding was that (1) there are different techniques the researcher can use in open coding such as the flip-flop technique and waving the red flag, (2) saturation, which occurs when no more patterns can be discovered from the data, is used as an indicator that coding should be stopped, since no additional codes are emerging. In

Glaser's version (Glaser, 1992), guidance for ceasing the coding effort is unclear.

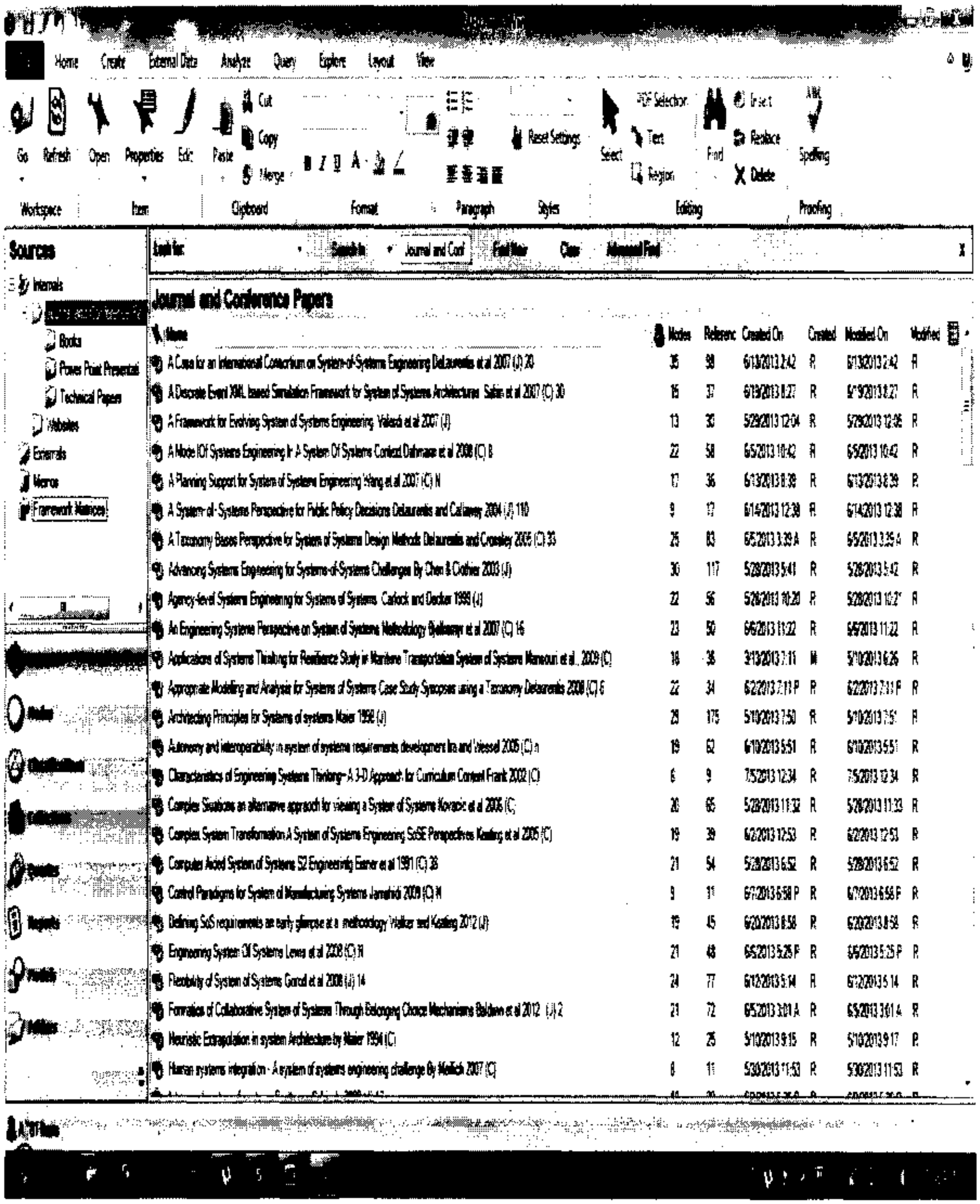
THE USE OF NVIVO SOFTWARE

Specific software, Nvivo (QRS International version 10, 2014) was used to conduct the coding procedure in this research. The following information provides the rationale for selecting this specific software:

- With the huge amount of data in this research, it is extremely difficult to navigate and manage manually. Therefore, the software capability to facilitate organization, traceability, tracking, and capture of data and subsequent analysis, was important in the decision for selection of the software.
- The Nvivo software, which helps to discover the connections in the dataset, was also supportive of the second coding mode, axial coding. Axial coding permitted discovery of the connections between the multiple codes. This coding was well supported by the Nvivo software.
- There are different techniques, supported by the Nvivo software, available to the researcher to assist in visualization of the data and discovery of patterns in the dataset.
- The power of Nvivo software is that it not only works with portable document format (pdf) and standard text documents (e.g. Microsoft Word) but also with audio recording, digital photos and video footage. In evaluation for software support selection, the researcher did not encounter difficulties in uploading any resource or format onto the software. Therefore, the support for analysis of in excess of one

thousand sources of literature was easily supported by Nvivo. Figure 3.2 provides a snapshot of Nvivo software.

Figure 3.2: A Snapshot of Nvivo



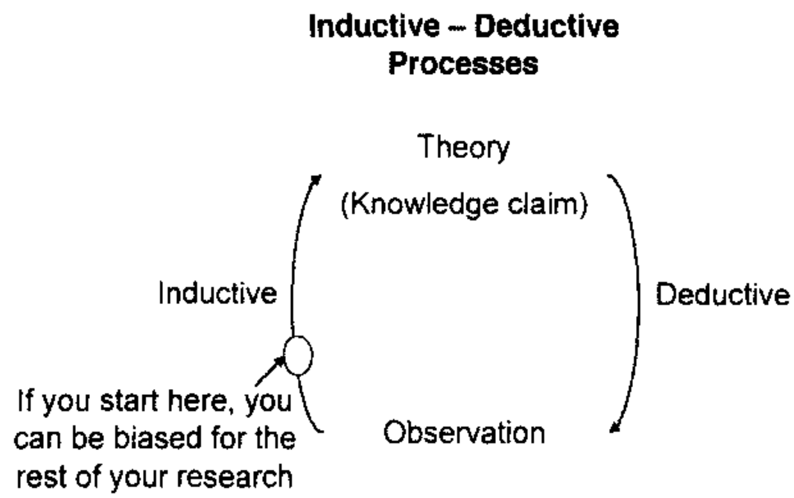
Nvivo software provided a powerful tool to support application of grounded theory coding essential to the research.

PHASE I OF THE RESEARCH DESIGN: THE DEVELOPMENT OF SYSTEMS THINKING CHARACTERISTICS

From the one thousand different resources, five hundred and fifty resources have been analyzed and coded in the first phase. The criterion that guided the selection of the five hundred and fifty materials was the works that contributed most to the complex system field as evidenced by the frequency of citation for the work. The purpose of this phase of research was to engage in open coding of literature in developing systems thinking characteristics. Given the many perspectives and articulations of what constitutes systems of systems (SoS) (Keating et al. 2003; Keating, 2005; Gorod et al. 2008), the researcher established a specific articulation of critical terms, including complex systems/SoS and system characteristics for purposes of this research. As mentioned earlier, the object of this first phase was to derive the set of systems thinking characteristics that could be construed as essential to enable individuals to effectively deal with complex problem domains.

The researcher conducted three main phases to answer the research questions and support achievement of the purpose of the research (Figure 3.1). The output of phase I was the production of a set of systems thinking characteristics. Because the research was building new theory (Figure 3.3), the researcher used an inductive reasoning approach to derive the taxonomy of systems thinking characteristics. As this figure indicates, the inductive approach is designed to build theory that in effect could be tested through deductive approaches.

Figure 3.3: Inductive and Deductive Reasoning



Lee and Baskerville (2003, p.224) stated that inductive reasoning "begins with statements of particulars and ends in a general statement." Phase I of the research design was qualitative in nature, and the researcher moved from particulars (the five hundred and fifty sources of the literature) to the general theory. Feibleman (1954) recommended using an inductive approach because it would result in a generalizable theory and would provide information that would be useful in future research. The researcher used an inductive approach for four main reasons: (1) the researcher aimed to develop an instrument that would be applicable across many fields including industrial, military, healthcare and others, (2) the researcher had no preconceived ideas about the set of the systems thinking characteristics, which is a critical element in inductive reasoning to support achieving a conceivable conclusion from the dataset, (3) the researcher's aim was to look for any patterns that emerged from the five hundred and fifty different sources under study, and (4) the inductive approach, focused on purposeful and deliberate building of understanding from the data, appeared the most appropriate for the purpose of this research.

After reviewing the literature on systems engineering, a common theme was that many studies show and propose personal characteristics of a good systems engineer (Trisha and Derro, 2007; Ryschkewitsch et al. 2009; Derro and William, 2009; Frank, 2006). Personal characteristics can be divided in two categories, those that are innate and those that can be learned and honed (Ryschkewitsch et al. 2009). All of these studies were restricted to a specific category of "systems engineer" within specific organization(s). While this literature, and corresponding conclusions, are insightful, the body falls short on the identification of what the characteristics are for performance of the systems thinking necessary to be a 'good' systems engineer.

In addition, the literature review of complex systems fails to identify a single study that identifies the systems thinking characteristics necessary for an individual to deal with multidisciplinary complex problem domains. *Therefore, the thrust of the research, and corresponding design, were supported. Ultimately, this design, in particular the Phase I research engaged a rigorous approach to: identify systems thinking characteristics essential to the complex problem domain.*

To fulfill the main objective of phase I, the researcher used five hundred and fifty different sources from the literature, as input for screening and grounded theory coding, to define a set of systems thinking characteristics. The literature provided essential help in framing the study and establishing validity support for the research instrument (Patton and Appelbaum, 2003). The following were the sources of data the researcher used to arrive at the set of systems thinking characteristics through the grounded theory coding process.

- *Histogram analysis of complex problems/SoS*. The histogram helped to classify and categorize the complex problems/SoS definitions and articulations to capture the set of systems thinking characteristics. The researcher used chronological order and selected the following criteria to construct the histogram analysis: (1) definitions for SoS, (2) characteristics for SoS, (3) methodologies for SoS and (4) principles and axioms for SoS. The histogram was structured based on the main contributions in the development of complex problems/SoS (Keating et al. 2003; DeLaurentis, 2005; DeLaurentis & Callaway, 2004; Keating, 2005). The histogram was constructed and thoroughly discussed in Chapter II.
- *The second source of data was based on the literature of system theory*. System theory was first introduced by von Bertalanffy (1948) prior to cybernetics, systems engineering and the emergence of related fields. This classical systems theory aims to state principles which apply to systems in general. These laws and principles can be found in a variety of source literature (Skyttner, 2001, 92-96; Clemson, 1984, 199-257; Ashby, 1947; Cherns, 1976; Smuts, 1926). The concept of system theory in this phase was focused primarily on systems principles, concepts, and laws to explore systems thinking characteristics the individual should possess to engage the multidisciplinary complex problem domains.

- *The third source of data for systems thinking characteristics was based on a survey of the systems thinking literature*. The concept of systems thinking in this phase was focused primarily on the several different definitions and methodologies concerning systems thinking.
- *The last source was based on a survey of different models in systems engineering* such as the NASA model and the Jet Propulsion Laboratory (JPL) model. These models delineated the characteristics of a good system engineer and gave the researcher some limited insight into structuring and deriving the proposed systems thinking characteristics.

As mentioned earlier, the researcher used the three sequential coding procedures in conducting grounded theory coding in phase I. The researcher adopted Strauss's Grounded Theory version to direct coding as discussed in Strauss and Corbin (1990). The following are the three coding procedures used for coding the included literature for the research to inform development of systems thinking characteristics as a necessary foundation for development of the instrument.

FIRST GROUNDED THEORY CODING PROCEDURE: OPEN CODING

Glaser and Strauss (1967) referred to the procedure for developing initial categories as open coding. Open coding, which applies codes to specific text, whole documents, etc., is a procedure used to link chunks of data together. The importance of open coding is that it ties directly to the data sources (complex systems/SoS, system theory, systems thinking and system engineering models) and codes the data until a particular concept occurs or derives, in this case an element for inclusion in the systems thinking characteristics. A number is applied to each code, and then the number of times that particular code (e.g. holism perspective as a system thinking characteristic) appears throughout the data sources is counted.

In the open coding procedure the researcher aimed to obtain numerical analysis (frequency of codes) from the dataset. It is necessary to mention that at the beginning of this procedure the researcher had no preconceived ideas about what would emerge from the dataset. However, during the open coding the researcher kept the following question in mind; *what are the patterns emerging from the data sources, through the open coding process, that support development of new theory?* In seeking to answer this question, the researcher remained open to exploring any new ideas or patterns in the data. The codes in this procedure reflect what the researcher inspected and observed in the data. For illustration purposes Figures 3.4, 3.5 and 3.6 show some of the codes that were obtained from three different sources (journal paper, book chapter, and technical report) in the literature during the open coding phase.

Figure 3.4: Codes from a Journal Paper

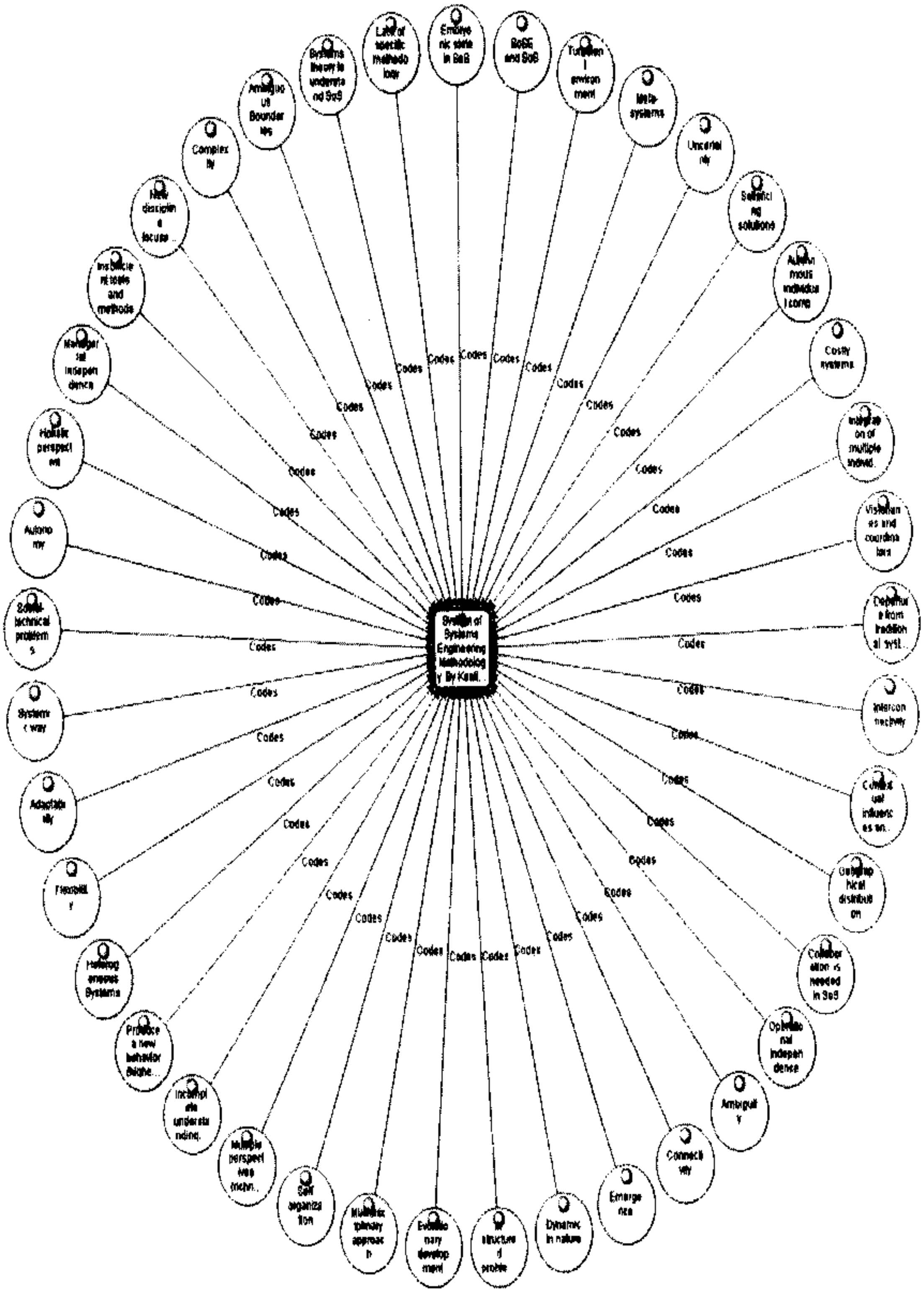


Figure 3.5: Codes from a Book Chapter

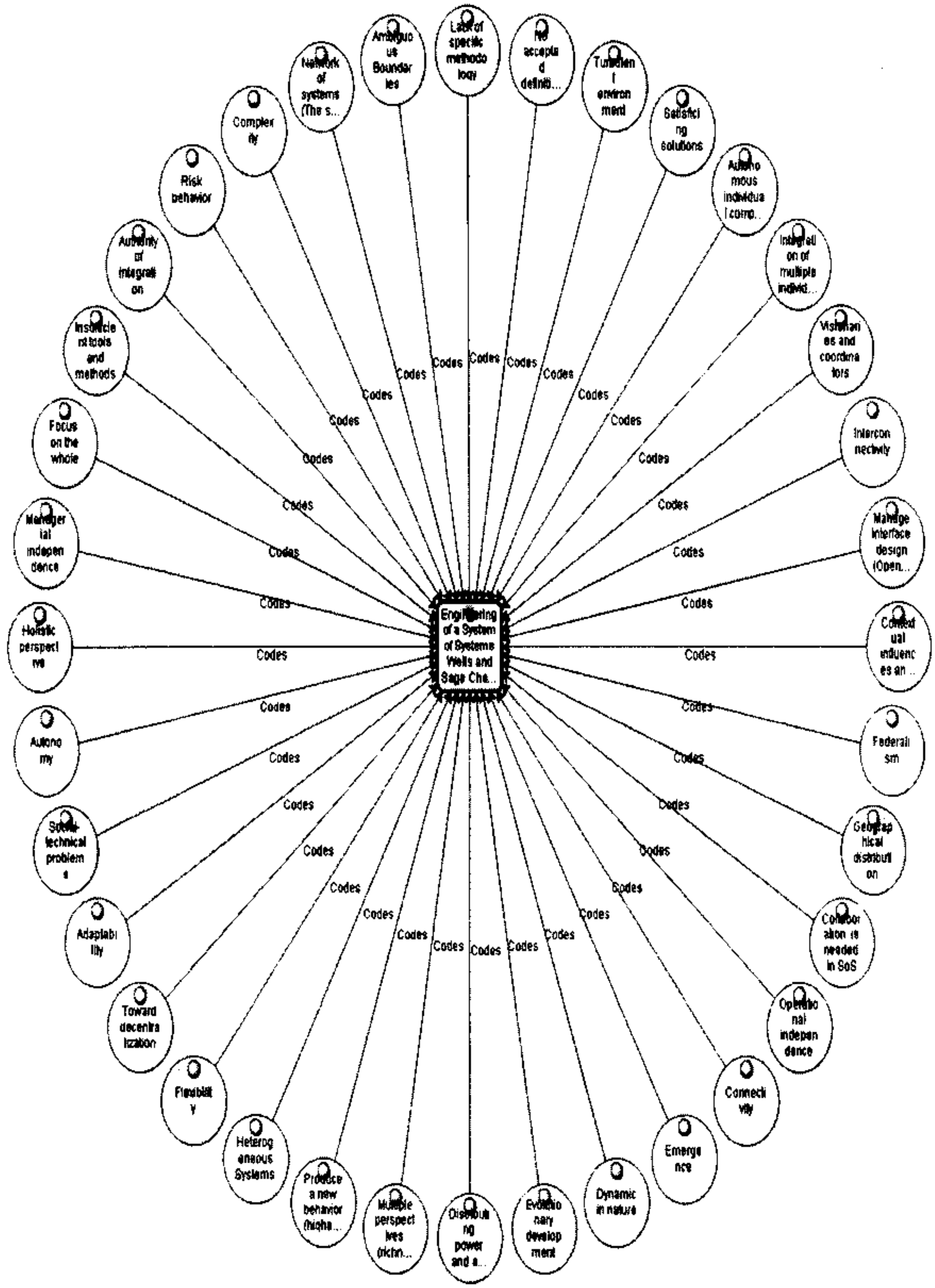
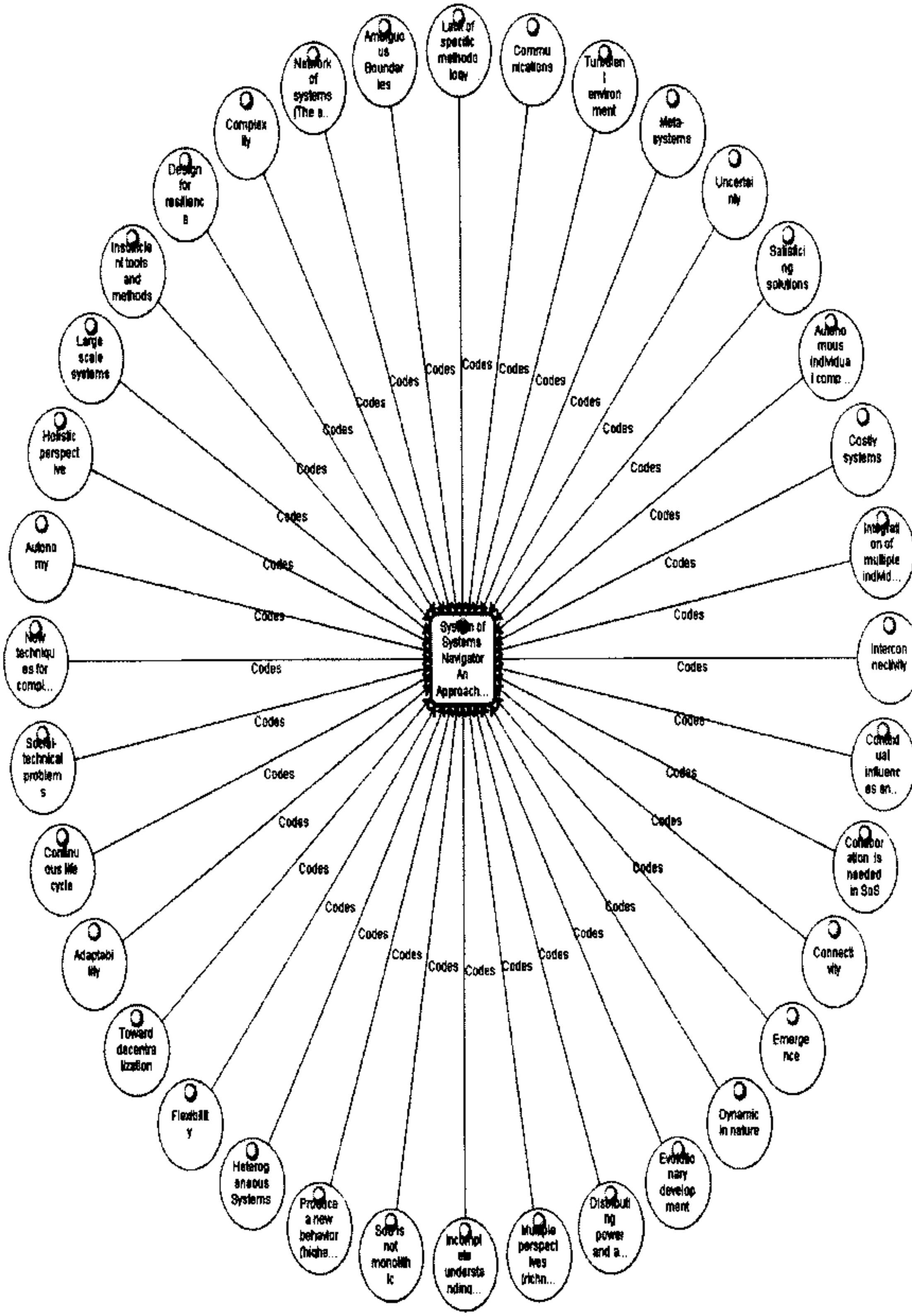


Figure 3.6: Codes from a Technical Report



These three figures illustrate how the researcher used the philosophy of "openness" inherent in open coding to capture as many patterns as possible in the dataset. To achieve a rigorous course of analysis in this coding procedure the researcher adhered closely to the data by:

1. Inspecting the data sentence by sentence and sometimes line by line,
2. Avoiding coding with words that are ambiguous or not clear in meaning, and
3. Avoiding any preconceived notion that might preclude new patterns from emerging.

The researcher approached the data with an open mind and with no preconceived ideas about the set of systems thinking characteristics that would emerge from interaction with the data and open coding process. Because of the overwhelming amount of data, it was important to remain focused and be aware of theoretical sensitivity (Glaser and Strauss, 1967) to determine what data was important in developing the new theory regarding systems thinking characteristics. Strauss and Corbin (1998) mentioned that theoretical sensitivity " helps the user recognize bias to some degree, and helps him or her overcome analytic blocks" (pp. 87-88).

During the analysis, the researcher attained theoretical sensitivity through deliberative immersion in the dataset using the sentence by sentence and line by line approaches along with the flip-flop technique, the red-flag technique and saturation specified in Strauss and Corbin (1990).

The researcher used the flip-flop technique to answer the six Ws; who, what, when, where, why, and how in the text. The following two examples are taken from Nvivo to explain how the flip-flop technique was used.

Table 3.1: Example One

Source: <Internals\\Journal and Conference Papers\\A Mode lOf Systems Engineering In A System Of Systems Context Dahmann et al 2008 (C) 8> - § 2 references coded [0.48% Coverage]
Text: "Finally, the environment changes during development, and unanticipated changes may have an overriding effect on user capabilities, further complicating the work of the systems engineer."
Flip-flop technique: What is emergence? When do unanticipated changes happen?
Code at: Emergence, Uncertainty

Table 3.2: Example Two

Source: <Internals\\Journal and Conference Papers\\Advancing Systems Engineering for Systems-of-Systems Challenges By Chen & Clothier 2003 (J)> - § 7 references coded [0.75% Coverage]
Text: It is important to acknowledge that in most cases, a Defense SoS is more likely a result of emergence or evolution.
Flip-flop technique: What is emergence? Why is a traditional system engineering method not appropriate in complex systems?
Code at : Emergence, Complexity

Using the flip-flop technique, the researcher looked at the words that seem significant such as the term "unanticipated changes" from example 3.1 and "emergence" from example 3.2 and tried to list all the possible codes pertaining to these terms in the text. In this procedure the researcher was not interested in discovering the connection between the "unanticipated changes" code and "emergence" code. The second procedure (Axial coding) explores the dimensions between the codes.

Waving the red-flag is the second technique the research adopted in this open coding procedure. Red flag means the researcher stops at specific phrases or words such as never, rarely, and always that lead to many questions. For example, the word "always" in example 3.3 makes the researcher certain that the environment in complex systems is difficult to grasp.

Table 3.3: Example Three

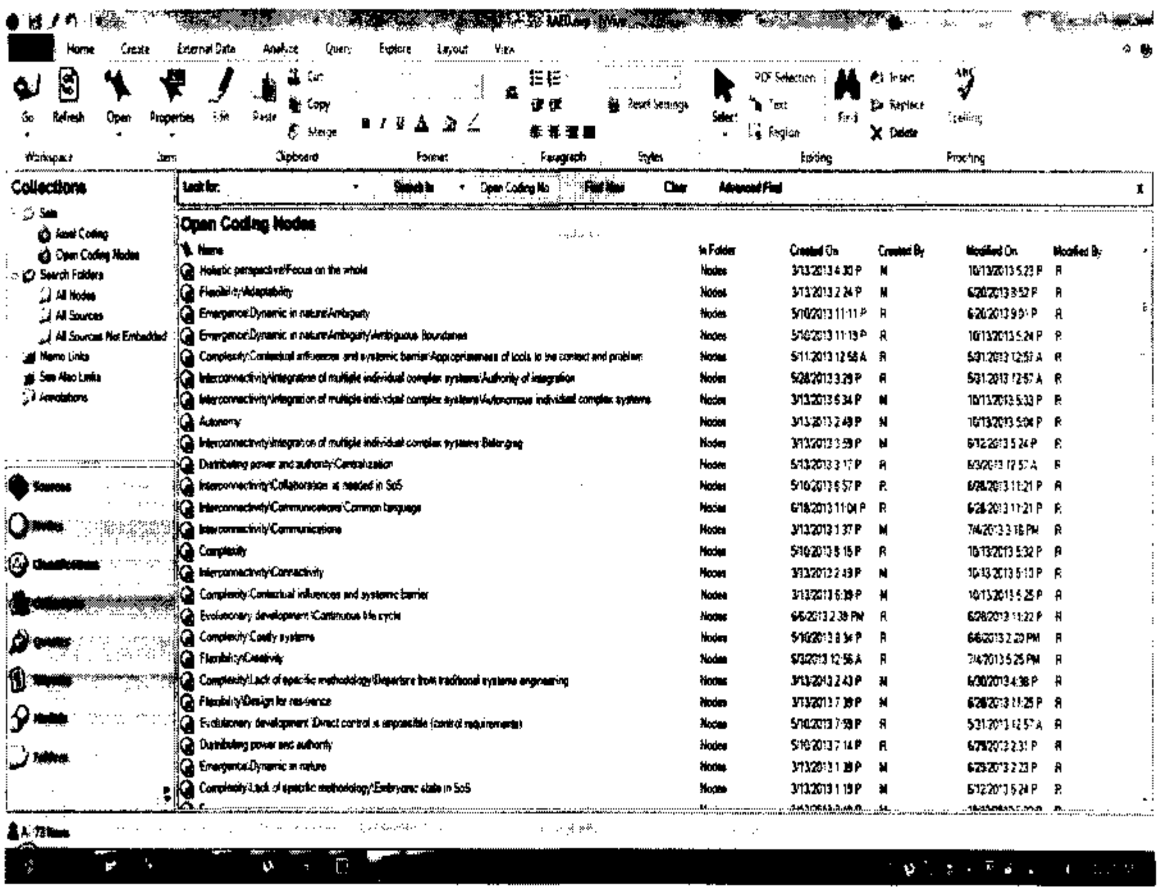
Source: <Internals\\Journal and Conference Papers\\Books\\From system of systems to meta systems ambiguities and challenges Djavanshir et al chapter 1 (2012)> - § 6 references coded [1.46% Coverage]
Text: The environment in which meta-systems are located is always uncertain and evolving.
Red-flag technique: Why is the environment in complex systems always uncertain?
Code at: Uncertain

The third technique the researcher used is saturation. The purpose of saturation, which comes at the end of open coding, is to avoid redundancies in the coding procedure. According to Charmaz (2006, p.113) "Categories are saturated when gathering fresh data no longer sparks new theoretical insights." Thus, the term "saturated" means that no new patterns can be defined in the data; therefore, no more coding will be applied. Saturation is the process that guided the researcher in making a decision regarding the right time to stop coding and move to the next procedure, axial coding.

In conducting the open coding, the researcher used some of the techniques that Strauss and Corbin (1990) have suggested. The flip-flop technique helped the researcher to think in critical ways by using the "what-if" analysis techniques. The red-flag technique alerted the researcher to look more closely at the dataset whenever there were sensitive words or phrases in the text such as "never, rarely, and impossible." It was recognized as important that the researcher pay careful attention to discovering the meaning of these words within a particular text. Although there are other techniques that could have been used, the researcher used the techniques that are most suitable for the dataset for this research.

At the end of the open coding procedure, the researcher coded a hundred codes from the different sources of the dataset. These are the 100 codes that are saturated, and there were no new ideas or patterns that can be added from the dataset meaning that there are no more variations in the selected dataset. Within the 100 codes, the researcher has looked into the most meaningful words that seem significant within the text. Figure 3.7 gives a snapshot of these codes (See Appendix A for a complete list of codes).

Figure 3.7: A Snapshot of Open Codes



Visualization of the first procedure: open coding

To have a clear visualization of the codes and to explore the patterns in the dataset, the researcher ran a tag cloud analysis and tree map analysis. The purpose of tag cloud analysis is to show the most frequently used words in the dataset and explore the coded content. The different font sizes represent the frequency of each word. The bolder the font, the more frequent the word. Figure 3.8 displays this analysis in alphabetical order.

Figure 3.8: Tag Cloud Analysis

A tree map analysis helps to compare the frequency of the different codes. The size and the color of the rectangles represent the area with the most coded codes. As illustrated in Figure 3.9 "Integration, Emergence, Autonomy, and Complexity" are the most frequent codes in the open coding procedure.

Figure 3.9: Tree Map Analysis

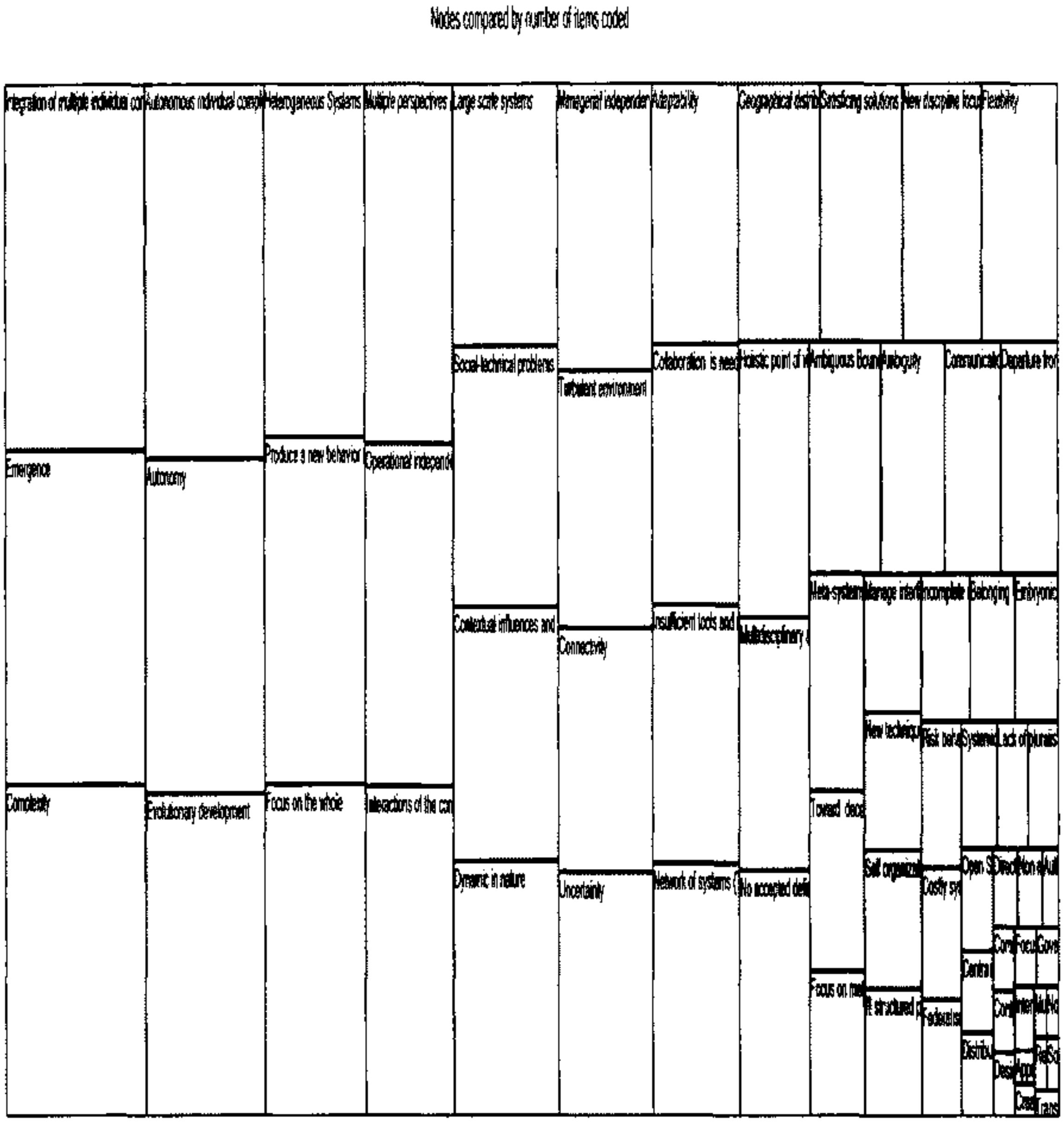


Table 3.4 provides a summary of the first grounded theory coding procedure, open coding

Table 3.4: Summary of Open Coding Procedure

	Open Coding
Purpose	Discover patterns in the dataset
Treatment of the dataset	Fracture the data into pieces by assigning several codes
Approaches used	Sentence by sentence and line by line analysis
Techniques used	Flip-flop, Waving the red-flag, and Saturation
Output	100 different codes

SECOND GROUNDED THEORY CODING PROCEDURE: AXIAL CODING

The second procedure in the grounded theory coding is axial coding (Strauss and Corbin, 1990). At the end of open coding, a set of complete codes were provided (Figure 3.9); however, this is not a final set of codes. Axial coding, which is created to serve as a filtering step, explores the correlations from open coding. In other words, it examines how the codes are related to one another. There were three main elements of axial coding:

- *Causal Condition:* describes the reason for having particular codes (categories) and shows the connections among the 100 codes. For example, what makes holism a system thinking characteristic appropriate for individuals to deal with multidisciplinary complex problems? In other words, what are the particular events that impact the phenomenon?

- *Phenomenon*: describes the central idea, namely, the set of systems thinking characteristics. The new theoretical development in this research is the set systems thinking characteristics proposed for an individual to effectively cope with complex problem domains. These characteristics are essential to assist in identifying individuals with the specific capabilities to more successfully navigate the complex problem domain.
- *Consequences*: represents the intended and unintended results of the new theoretical development, that is, the systems thinking characteristics.

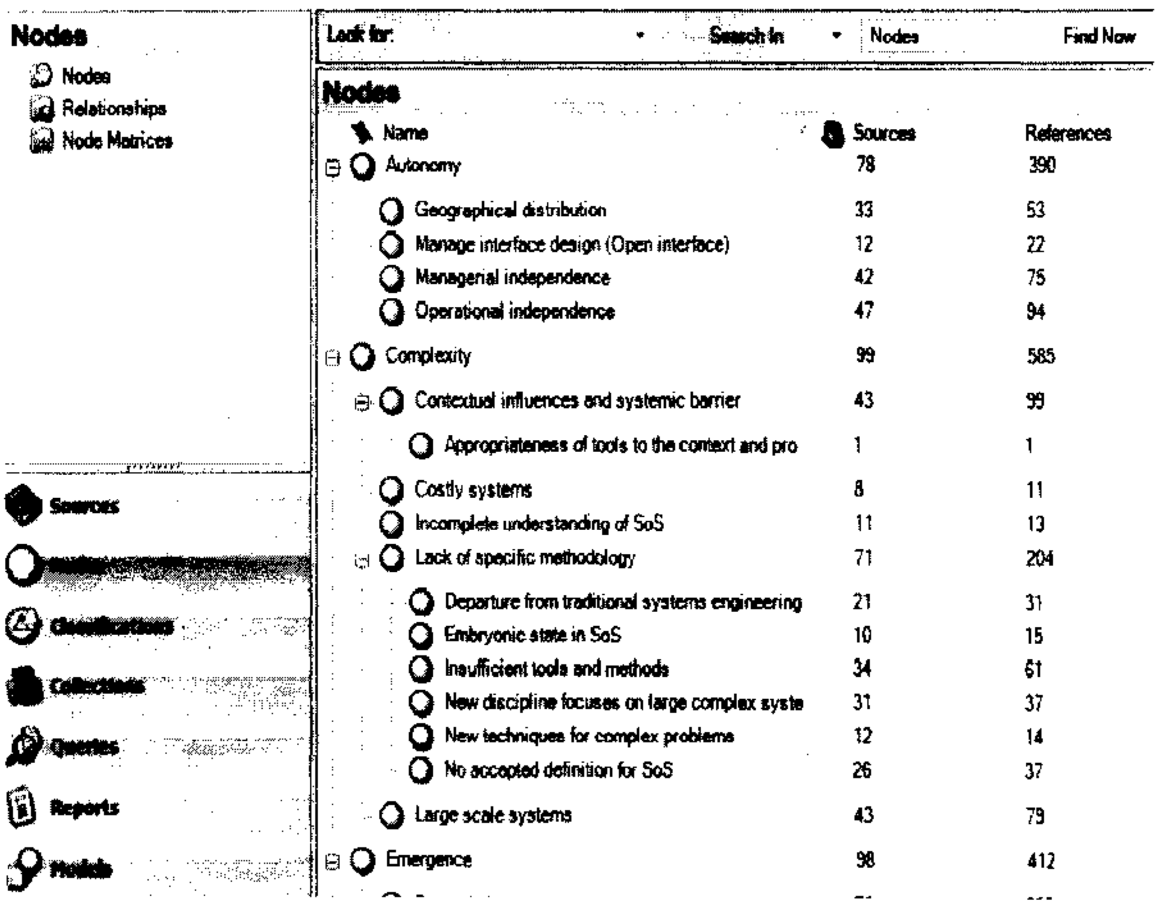
Charmaz (2006) clarified that focused coding (axial coding) "means using the most significant and/or frequent earlier codes to sift through large amounts of data." (p.57). In the open coding procedure the researcher has fractured the dataset gleaned from five hundred and fifty different sources by establishing sentence by sentence and line by line analysis. In the axial coding procedure, the researcher synthesized the dataset into a large segment. According to Strauss and Corbin (1990) the object of axial coding is to put "the fractured data back together in new ways." [as cited by Walker and Myrick, (2006), p.553]. This procedure builds and delineates the relationships between categories (codes) and connects the categories to their subcategories (Strauss, 1987). In this research axial coding was used to:

1. Synthesize the fractured data (distinct codes) into a large set (or coherent whole) by assigning categories and subcategories,
2. Connect and relate the categories to subcategories,

3. Explore and organize the categories by showing the reasons for these specific categories and their relationships, and
4. Build a theoretical coding paradigm showing the relationships.

In this second coding procedure the researcher started making connections between the 100 codes in the dataset and began to delimit the 100 codes around main categories. To do this, the researcher used causal conditions and central phenomenon as a frame of reference to explain how and why some categories, or codes, are related and linked to other subcategories called child-codes. Figure 3.10 shows how some of the 100 codes have been connected to one other and linked to other subcategories as well.

Figure 3.10: Axial Coding Codes

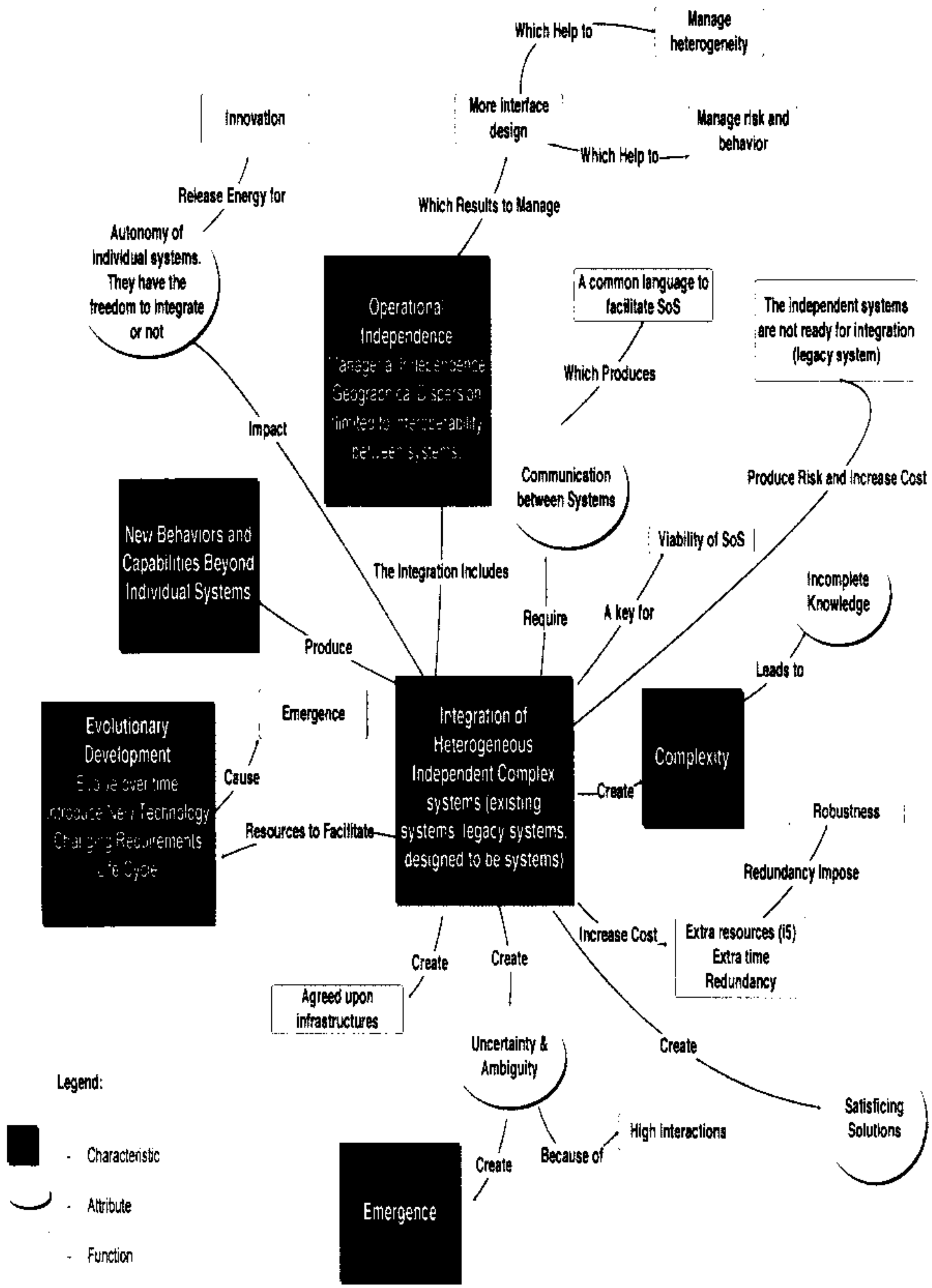


In this sample, "Autonomy" is considered a main category or parent node and "geographical distribution, manage interface design, managerial independence, and operational independence" are the subcategories referred to as child nodes. In the axial coding procedure, the researcher identified 30 main categories (parent nodes) among the 100 codes. Conceptual model, Model coding analysis, Coding query, and Matrix coding analysis were adopted to show the rationale behind selecting the 30 categories (codes) and their subcategories. Each of these approaches is described below.

The following four points explain the reasons of selecting the 30 categories:

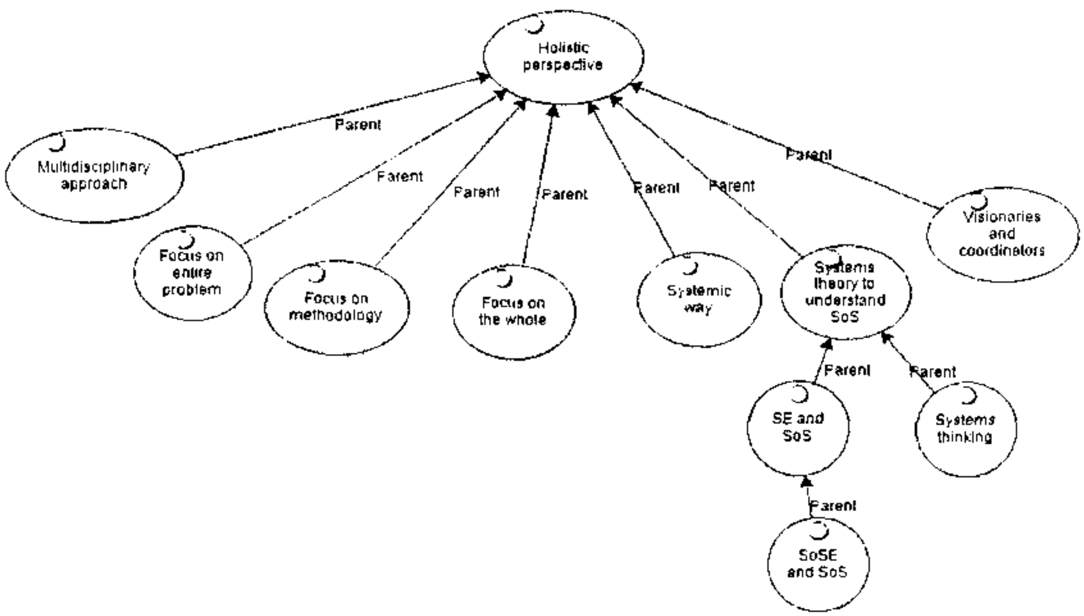
1. Constructing a histogram analysis as discussed in Chapter II, the researcher conducted an in-depth analysis which enabled him to create a conceptual model showing the connections and relationships among the 100 codes (categories) and their subcategories (Figure 3.11).

Figure 3.11: Conceptual Model of the 100 Codes and their Relationships



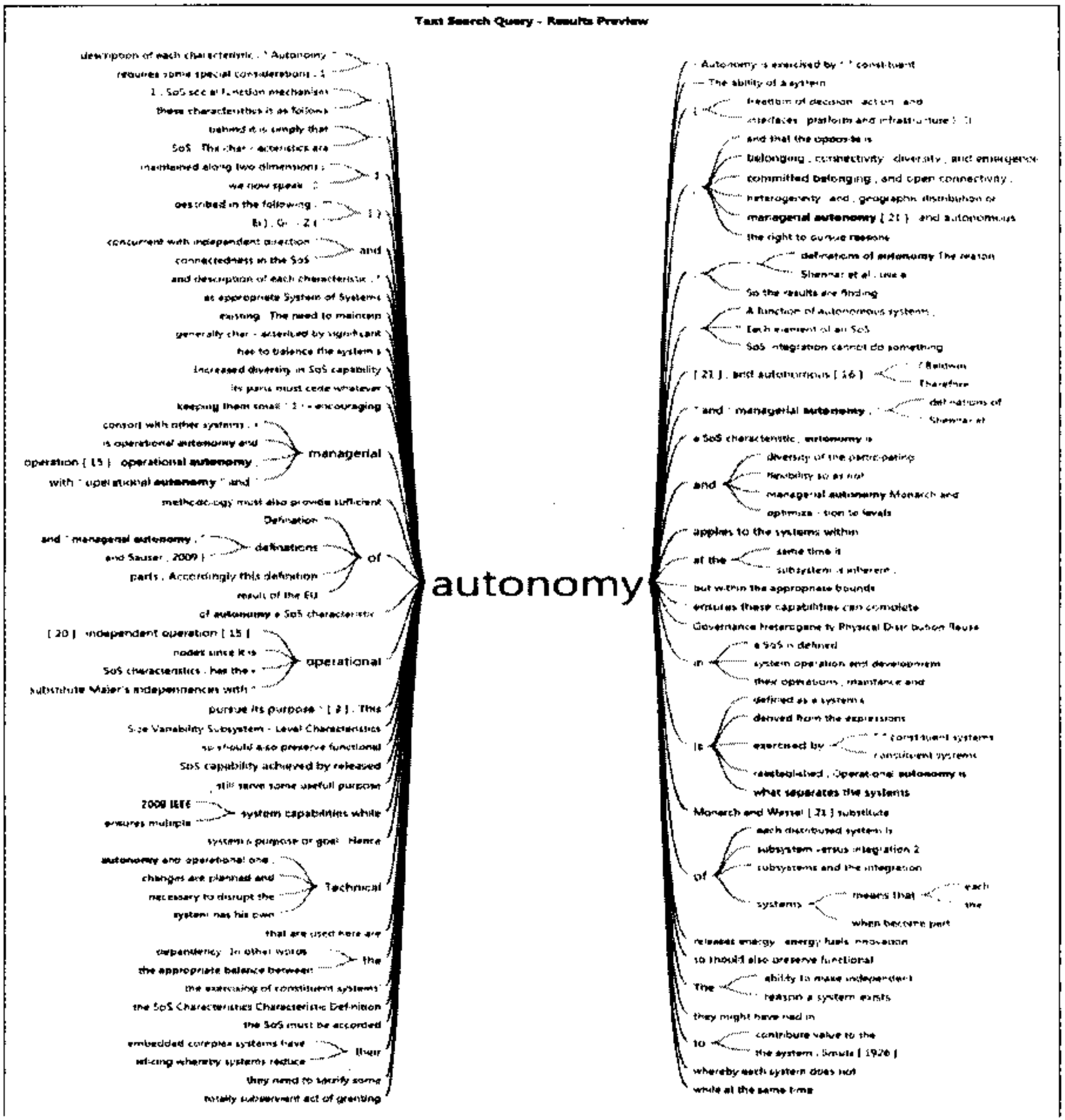
2. Model coding analysis, a feature in the Nvivo software, was used to compare and explore the connections across the different categories and their subcategories (100 codes). Figure 3.12 depicts how "Holistic Perspective" as a main category (parent node) is linked and related to other subcategories (child node).

Figure 3.12: Model Coding Analysis



3. Coding query is another way to check the connections among the nodes (Figure 3.13). Coding query can answer questions such as how different scholars define autonomy. From the tree analysis (Figure 3.9), it is clear that the definition of autonomy includes operational independence, managerial independence, and geographical distribution. This explained why "Autonomy" as a parent node contains the child nodes operational, managerial, and geographical distribution. These child nodes are the subcategory of the main category "Autonomy" as shown in Figure 3.13.

Figure 3.13: Coding Query Analysis



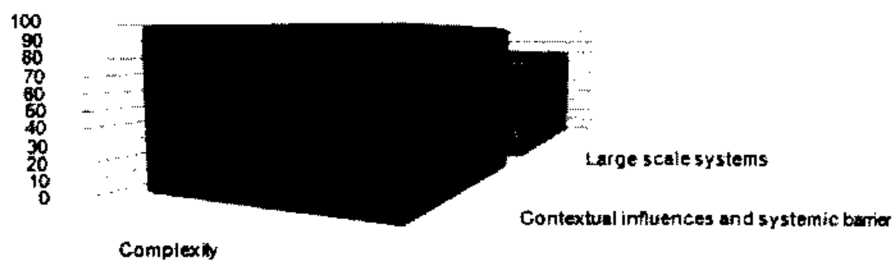
4. Matrix coding query is another way the researcher tested the connections among the categories (nodes) and their subcategories. Matrix coding allows comparison of

coded source materials across the nodes (QSR International version 10, 2014) and explores the coded content in the source of the dataset. This analysis answers questions such as whether there is a connection between complexity, contextual issues, and large scale systems. To answer this question the researcher ran matrix analysis to cross tabulate and compare the coded content that included both complexity node, contextual issues node, and large scale node. Figure 3.14 and Table 3.5 demonstrates these connections.

Table 3.5: Matrix Coding for Complexity Node

	A : Complexity
[redacted]	112
[redacted]	83

Figure 3.14: Matrix Coding Analysis



The rows represent the subcategories for the main category "complexity". Each cell contains the number of intersecting coding references. For example, there are 112 references concerning the connection between complexity and contextual issues which led to the researcher's considering contextual issues as a child node for complexity.

Although the Strauss and Corbin's framework in the axial coding procedure could have been used, the researcher chose an alternate method and showed his rationale for developing and selecting the 30 main categories and relating them to the subcategories. As Straus and Corbin (1998) wrote, the paradigm "is nothing more than a perspective taken toward the data." (p. 128). Table 3.6 provides a summary of the second coding procedure, axial coding.

Table 3.6: Summary of Axial Coding Procedure

	Axial Coding
Purpose	Connect and link the codes from the previous procedure (Open Coding)
Treatment of the dataset	Treat the data as a whole unit
Elements used	Causal conditions Central phenomenon
Techniques used	Conceptual Model, Model Coding Analysis, Coding Query, and Matrix Coding analysis
Output	30 categories (codes)

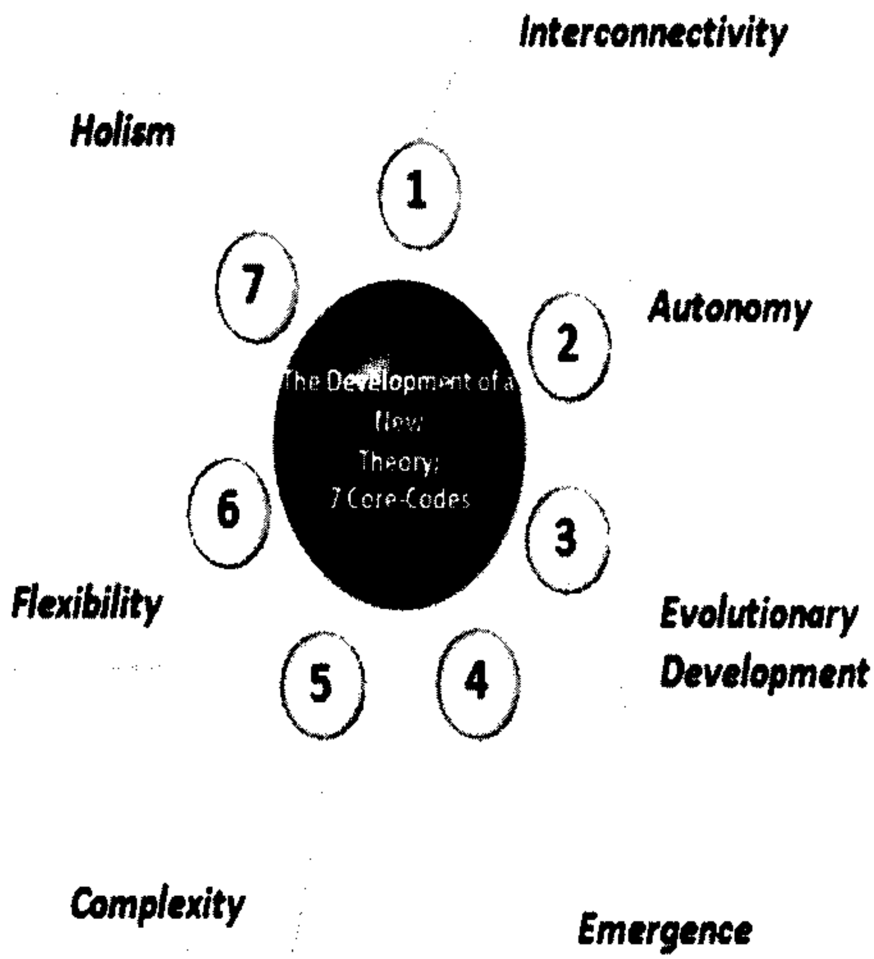
THIRD/FINAL GROUNDED THEORY CODING PROCEDURE: SELECTIVE CODING

This is the final procedure in the grounded theory coding schema. The purpose of selective coding is to choose the best code or codes as the core category and relate all other codes to that category. In this procedure the researcher is required to integrate all of the data around a central theme to generate a theory (Walker and Myrick, 2006). For example, if "holism perspective" is selected to be code number 1 and "treatment of complex system as a whole unit" is labeled as code number 2, then the selective coding procedure would identify code number 1 to be the core category. All other correlated codes (code 2) will be related to the core category.

In the selective coding procedure the researcher chose the seven core codes that form the theoretical framework (central phenomenon of the research). These seven core codes, identified as Interconnectivity, Autonomy, Evolutionary Development, Emergence, Complexity, Holism, and Flexibility, form the building blocks for developing a new theory (Figure 3.15).

> *In this final coding procedure a theoretical model has been developed and a new theory is obtained. This theory is the set of systems thinking characteristics (7 core-codes) that determine an individual's predisposition to dealing successfully with the complex problem domain.*

Figure 3.15: 7 Core-Codes



The 7 core codes were derived after scrutinizing the patterns in the dataset using three main coding procedures: open coding, axial coding and selective coding. The discussion of the core codes as findings from application of the research design will be elaborated upon in the following chapter.

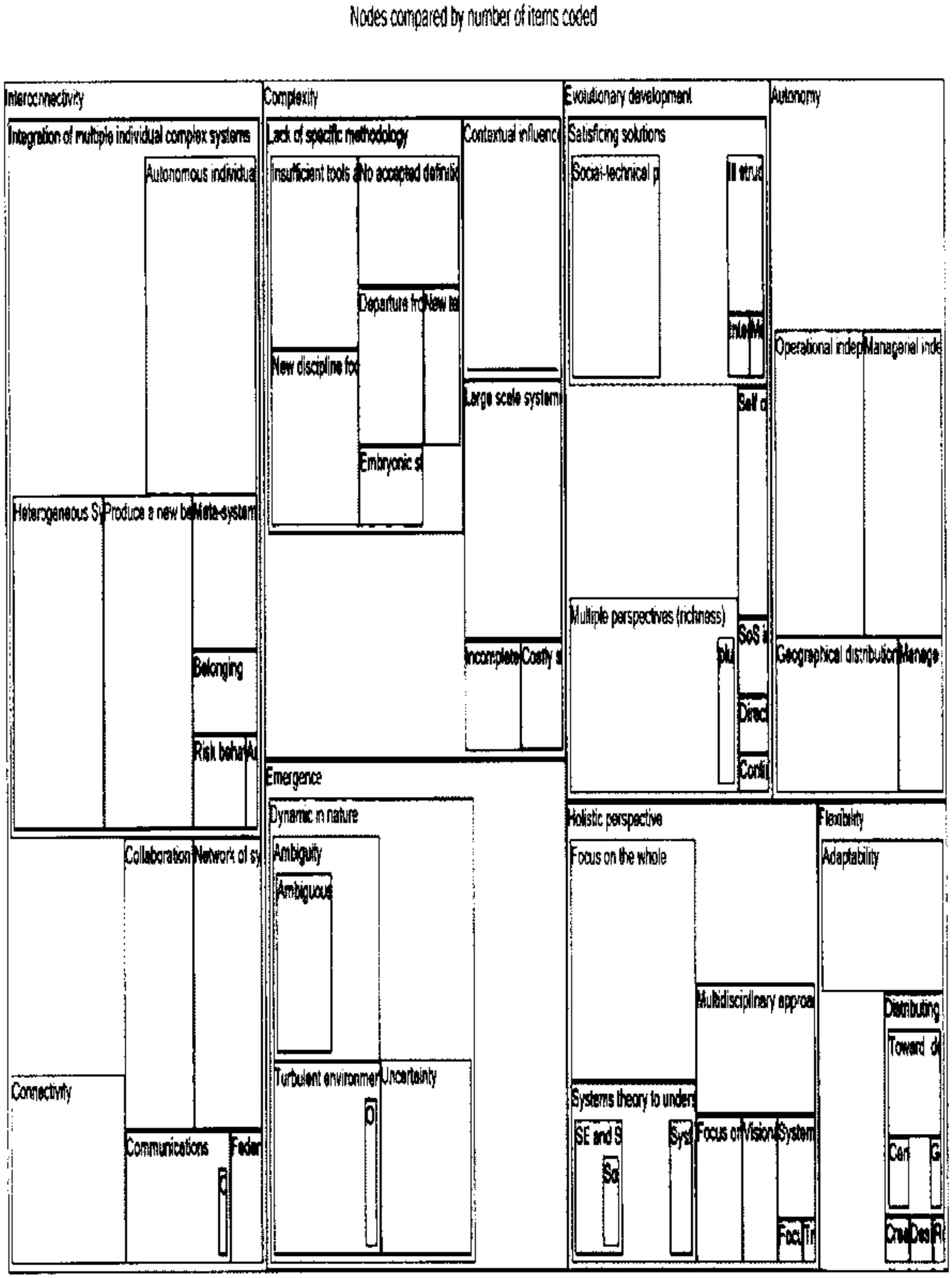
Visualization of the last procedure: selective coding

To visualize the 7 core-codes, the researcher used tree map analysis and cluster analysis. As with the open coding visualization, the size and color of the rectangles indicate the codes with the higher coded content. This analysis is effective in exploring the dominant categories (codes) in the dataset and the connections between them. Table 3.7 shows the number of items coded for one core-code, "Autonomy". These are the number of items coded to derive "autonomy" as one characteristic of systems thinking. In addition, Figure 3.16 exhibits the 7 core-codes with their sub-codes.

Table 3.7: Coding References

Nodes	Number of items coded
Nodes\\Autonomy	623
Nodes\\Autonomy\Geographical distribution	133
Nodes\\Autonomy\Manage interface design (Open interface)	122
Nodes\\Autonomy\Managerial independence	145
Nodes\\Autonomy\Operational independence	223

Figure 3.16: Tree Map Analysis for the7 Core-Codes



While the tree analysis explained the dominant categories and the connections between them, the cluster analysis was used to check for similarities and differences and how the five hundred and fifty different sources have been coded (Nvivo QRS International version 10, 2014). Figure 3.17 shows a sample cluster analysis dendrogram of the 7 core codes. The different colors indicate the coding similarity across the 7 core codes using the Pearson Correlation Coefficient. For example there is a correlation between Evolutionary development and Dynamic in nature based on the gray color

Figure 3.17: Cluster Analysis of the 7 Core-Codes

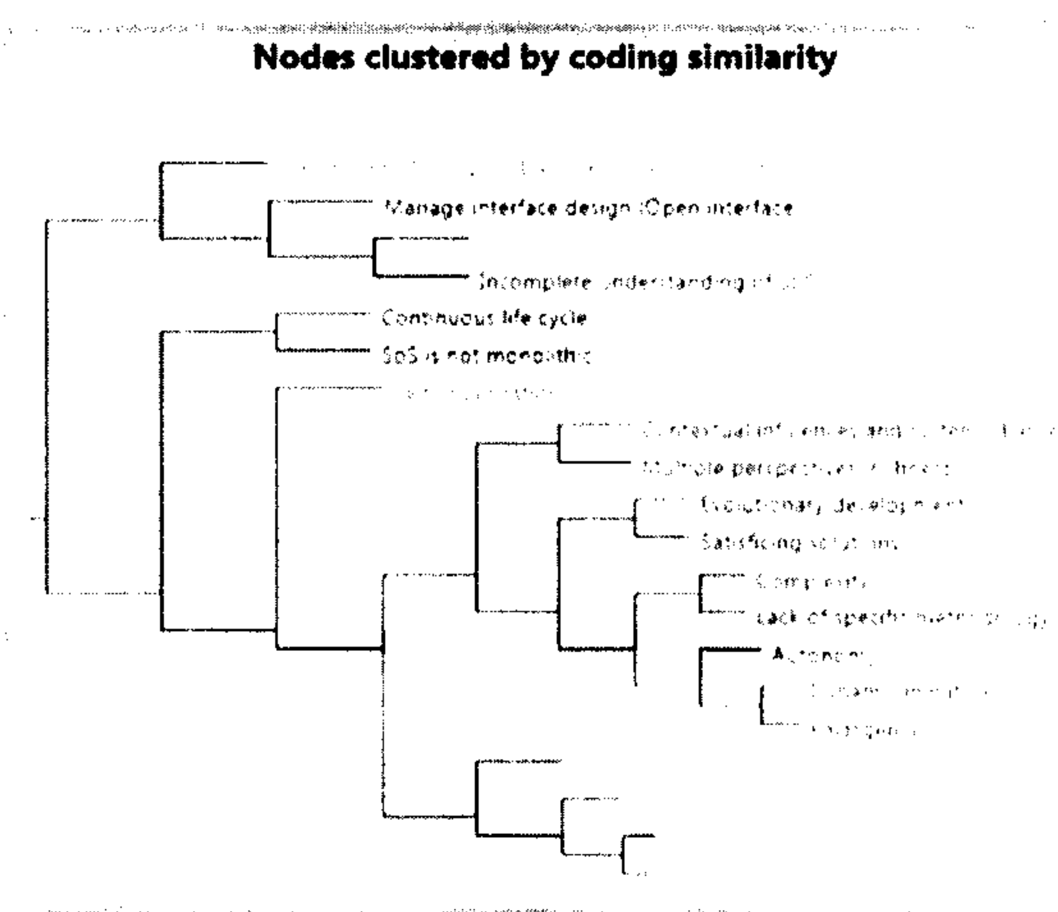
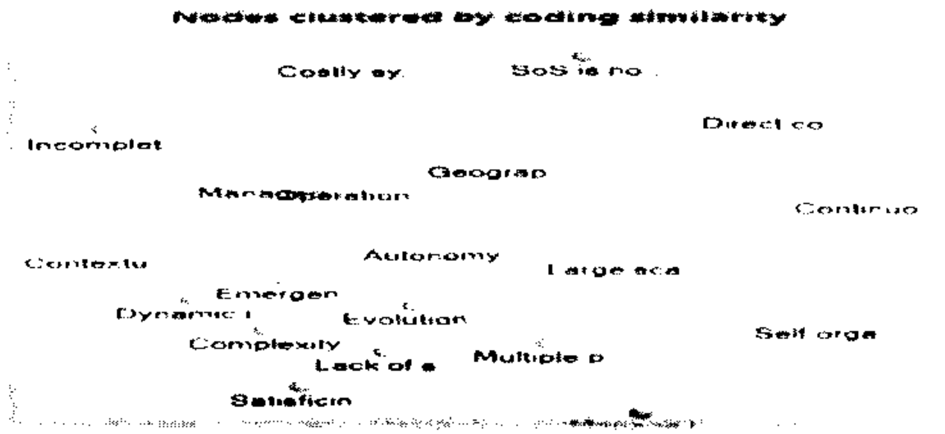


Figure 3.18 show a cluster analysis diagram of the 7 core codes using a 3D diagram.

Figure 3.18: Cluster Analysis of the 7 Core-Codes (3D)



Using grounded theory procedures of open coding, axial coding, and selective coding, a new theory has emerged involving the set of systems thinking characteristics that are proposed for an individual to effectively cope with complex problem domains (Figure 3.15). The new theory consists of one alternative hypothesis which is tested against the null hypothesis. Chapter IV is allotted to analyzing the data and testing the hypothesis which is stated below.

H_1: *there is a statistically significant relationship between the proposed systems thinking characteristics and the state of systemic thinking at the individual level that would indicate predisposition for engaging in the complex problem domain.*

It is important to mention that while conducting the coding procedures, the researcher also wrote various memos and analytic notes which were useful in making constant comparisons among the dataset and maintaining connection between the codes. According to Walker and Myrick (2006), writing memos is an efficient way to record any conceptual or theoretical ideas that may form during the analysis. In addition, during the course of analysis, the researcher used coding strips to keep track of the codes and highlighted the coded contents. Figure 3.19 is a snapshot of the coding strip procedure. The density bar shows all codes within this document. The darker the bar, the more coding there is (Nvivo QRS International version 10, 2014).

Figure 3.19: Coding Strip

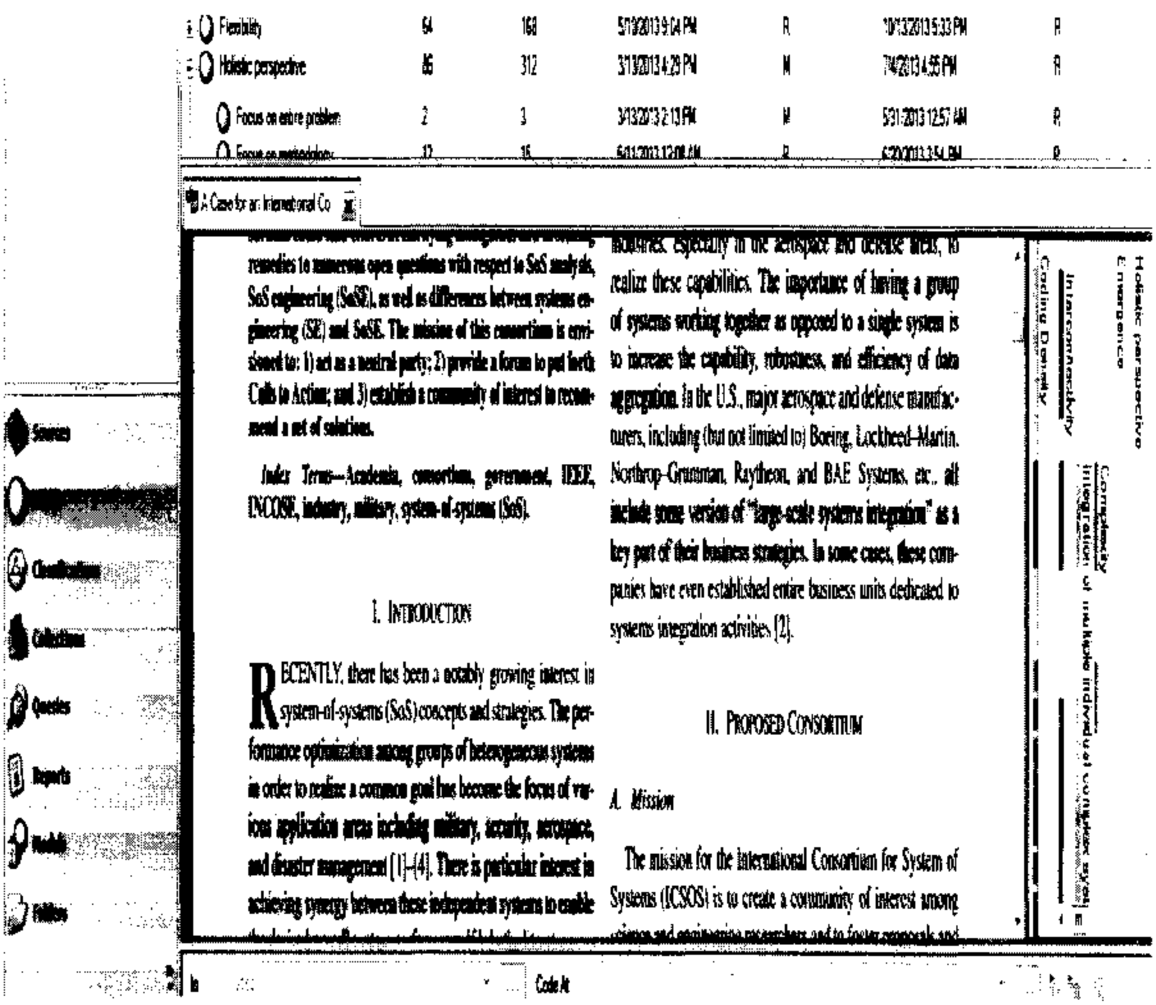


Table 3.8 provides a summary of the last coding procedure, selective coding.

Table 3.8: Summary of Selective Coding Procedures

	Selective Coding
Purpose	Determine the core-codes
Treatment of the dataset	Treat the data as a whole unit
Techniques used	Tree Map and Cluster Analysis
Output	The development of a new theory consisting of one hypothesis

PHASE II: APPLYING THE 7 CORE-CODES (SYSTEMS THINKING CHARACTERISTICS) TO INDIVIDUALS

This phase of research consists of two steps: first, providing a comprehensive definition for each of the 7 core codes (systems thinking characteristics) and second, applying the set of systems thinking characteristics to be suitable for individuals

FIRST STEP IN PHASE II PROVIDING A COMPREHENSIVE DEFINITION FOR EACH OF THE SYSTEMS THINKING CHARACTERISTICS

Figure 3.20 and Table 3.9 below depict the weighting score systems thinking characteristics received in the coding process. For example, the attribute "Interconnectivity" (randomly assigned #1) coded 869 times within 550 different sources from system theory, complex systems/SoS, models of systems engineering, and systems thinking.

Figure 3.20: Sc Characteristics Coding Scores

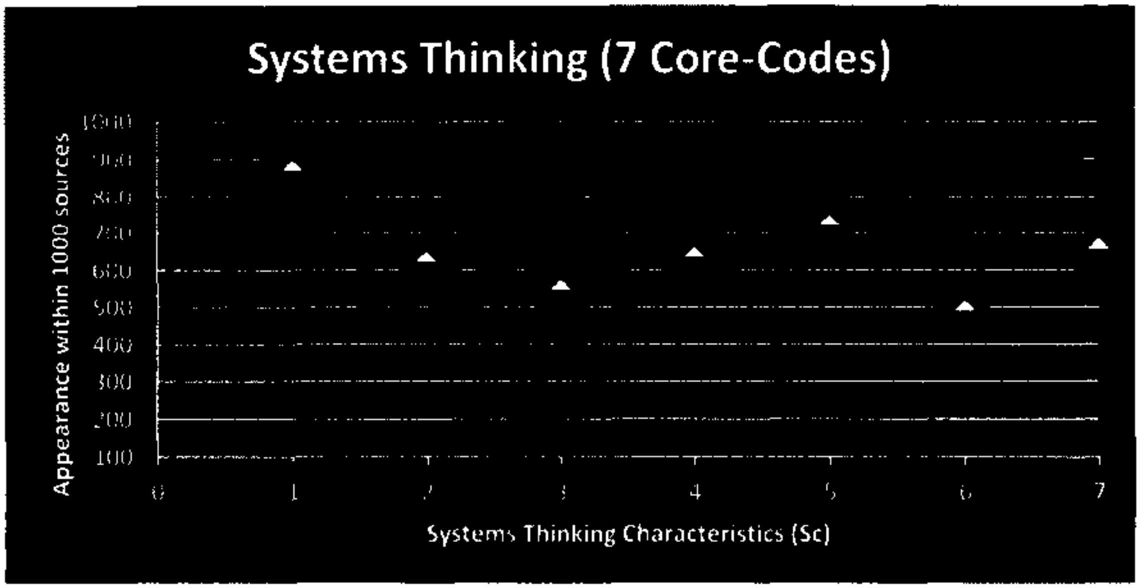


Table 3.9: Coding Scores

Systems Thinking SC 7 Core Codes	Coding	Number
Interconnectivity	869	Sc1
Autonomy	623	Sc2
Evolutionary development	546	Sc3
Emergence	634	Sc4
Complexity	720	Sc5
Flexibility	488	Sc6
Holism	657	Sc7

To apply these systems thinking characteristics to individuals, it is necessary to provide each characteristic with a comprehensive definition based entirely on the 550 different sources. The seven core codes and their definitions are provided in the following pages.

Interconnectivity (869 coded contents)

System of systems (SoS) comprises multiple autonomous heterogeneous systems integrated into a large system to produce new behaviors and unique capabilities that are not achievable by any constituent system. The integration might include: (1) existing systems, (2) legacy systems (retired), (3) yet to be designed systems (new systems), (4) hybrid systems, or (5) partially developed systems. These systems integrate regardless of their heterogeneity. Large complex systems are composed of heterogeneous systems involving people, information, human/social and cultural identities, technology, hardware and software, and multiple perspectives. The constituent systems and their components contribute to the larger mission of the larger complex system and enlarge its capabilities.

To produce new behaviors and capabilities, the heterogeneous constituent systems need to interact, collaborate, and communicate among themselves as well as each other. This combined interaction includes: (1) interaction with each other and with the surrounding environment, (2) human interaction derived from social-technical problems, (3) interaction between the systems' components, namely hardware and software, and (4) interaction involving the collection and flow of data. Because of the complexity, uncertainty, ambiguity and dynamic nature of complex systems problem domains which are by nature ill structured and multidimensional, it is fairly difficult to find an optimal solution to the problem. Instead, there are a set of potential satisficing comprehensive solutions.

Cross references (Kotov, 1997; Maier, 1998; Delaurentis et al. 2007; Baldwin and Sauser, 2009; Sauser and Boardman, 2008b; DeLaurentis and Crossley, 2005b; Sahin et al. 2007a; Dahmann et al. 2005; Keating, et al. 2003; Shain et al. 2007b; Shenhar, 1994; Carlock and Fenton, 2001; Sage and Cuppon, 2001; Chen and Clothier, 2003; Bar-Yam, 2004; Gorod et al. 2007; Jamshidi, 2008; Maier, 1994; Dagli and Ergin, 2008; Lane and Valerdi, 2007; Eisner, 1993; Keating et al. 2005; Pei, 2000; Crossley, 2004; Maier, 2005; Jamshidi, 2008; Carlock et al. 1999; Keating, 2005).

Autonomy (623 coded contents)

Individual systems that constitute large complex systems (SoS) have their own useful purpose for existing even after they are detached from the SoS network. Autonomy includes levels of operational, managerial, or geographical dispersion. In other words, they control their own decisions, actions, and interpretations (Keating, 2009).

Operational autonomy: the capability of each individual system within SoS to operate independently to fulfill a purposeful goal and behavior.

Managerial autonomy: each individual system is "separately acquired and integrated" [Maier, (1998), p.271) and maintains an operational existence (Sage and Cuppon, 2001).

Geographical dispersion: the sharing of information and data (interoperability) but not physical entities.

The integration of SoS dictates that the individual systems sacrifice some degree of autonomy to achieve the overall purpose (Krygiel, 1999).

Cross References (Keating et al. 2008; Sage and Cuppon, 2001; Krygiel, 1999; Maier, 1998; Keating, et al. 2003; Shain et al. 2007; Shenhar, 1994; Carlock and Fenton, 2001; Chen and Clothier, 2003; Bar-Yam, 2004, Gorod et al. 2007; Jamshidi, 2008; Maier, 1994; Dagli and Ergin, 2008; Lane and Valerdi, 2007; Eisner, 1993; Bar-Yam, 2004; Keating et al. 2005; Pei, 2000; Crossley, 2004; Maier, 2005; Clark, 2009; Carlock et al. 1999; Chattopadhyay et al. 2008; Lane and Boehm, 2008; Maier, 1996; Manthorpe, 1996; McCarter and White, 2009; Northrop et al. 2006).

Evolutionary Development (546 coded contents)

Large complex systems change over time because they interact with the surrounding environment. Thus, a SoS cannot be treated as a monolithic system. This evolutionary development includes: (1) changes in technology, (2) evolving needs and requirements, (3) an evolving social infrastructure, (4) a continuous life cycle and the sum of constituent systems' life cycle, (5) the redesign, redevelopment, modification or improvement in the system's structure and/or behavior), (7) uncertain resources and the diversity of multiple perspectives (8) the emergence of unintended behavior, and (8) fluid boundaries and uncertainty.

Cross references (*Delaurentis, 2005; Jackson and Keys, 1984; Lukasik, 1998; Rebovich, 2008; Sauser et al. 2008; Maier, 1998; Keating et al. 2004; Sage and Cuppon, 2001; Bar-Yam, 2004, Gorod et al. 2007; Jamshidi, 2008; Maier, 1994; Dagli and Ergin, 2008; Lane and Valerdi, 2007; Eisner, 1993; Chen and Clothier 2003; Keating et al. 2005; Maier, 1996; Manthorpe, 1996; McCarter and White, 2009; Northrop et al. 2006; Pei, 2000; Crossley, 2004; Maier, 2005)*

Emergence (634 coded contents)

Emergence can be described as unpredicted behaviors/patterns resulting from the integration and the dynamic interaction between the constituent systems, their parts and the surrounding environment (open systems). These behaviors/patterns cannot be anticipated beforehand and cannot be attributed to any of the constituent systems. These behaviors/patterns evolve over time and none of the constituent systems are capable of producing these behaviors in isolation. These unforeseen behaviors occur because of the uncertainty, high level of interaction, ambiguity, and complexity in large complex systems.

Cross references (Delaurentis et al. 2007; Maier, 1998; Keating et al. 2008; Hitchins, 2003; McCarter and White, 2008; Wells and Sage, 2009; Checkland, 1993; Bar-Yam, 2004, Gorod et al. 2007;

Jamshidi, 2008; Maier, 1994; Dagli and Ergin, 2008; Lane and Valerdi, 2007; Maier, 1996; Manthorpe, 1996; McCarter and White, 2009; Northrop et al. 2006; Pei, 2000; Crossley, 2004; Eisner, 1993; Sage and Cuppon, 2001; Chen and Clothier 2003; Keating, 2005;Maier, 2005)

Complexity (720 coded contents)

Complex systems are defined as those that include: (1) large scale systems and components, (2) huge data collection and data flow, (3) individual systems that are themselves complex with a large number of entities, (4) a high level of interrelationships among the individual systems and their components, (5) multiple perspectives, (6) new fields lacking specific methodology, (7) autonomous individual systems, and (8) contextual issues of a dynamic nature. Contextual issues entail specific external influences, characteristics, or conditions that influence and constrain the solution and the deployment of the solution. These constraints may include the following dimensions: political, managerial, social and cultural, financial (resources/funding), organizational, technical dimensions, and/or related to policies. Together, these characteristics lead to uncertainty, ambiguity, and incomplete knowledge and, consequently, increase the complexity in large complex systems (SoS).

Cross references (Keating et al. 2008; Sauser et al. 2008; Carlock and Fenton, 20001; Eisner, 1993; Sage and Cuppon, 2001; Chen and Clothier, 2003; Bar-Yam, 2004; Maier, 1996; Manthorpe, 1996; McCarter and White, 2009; Northrop et al. 2006; Gorod et al. 2007; Jamshidi, 2008; Maier, 1994; Dagli and Ergin, 2008; Lane and Valerdi, 2007; Keating, 2005; Pei, 2000; Crossley, 2004; Maier, 2005; Carlock et al. 1999; Beer, 1981; Baldwin and Sauser, 2009; Azani and Khorramshahgol, 2005; Alison and Cook, 1998; Allport, 1937; Ashby, 1947; Ackoff, 1971, Ackoff, 1995).

Flexibility (488 coded contents)

The design of large complex systems should be flexible so that it can adapt and respond in a cost-effective manner to any condition arising from emergence, turbulent environments, uncertainty, and contextual issues of a dynamic nature. Flexibility is the ability to add, adjust or remove both physical components and functions. The level of flexibility should not cause the SoS to lose its identity; rather, it should provide an environment of trust where individuals can share their initial plans and strategies.

Cross references (Gorod et al. 2008; Chen and Clothier, 2003; Maier, 1998; Adams, 2011; Keating et al. 2004; Keating et al. 2008; Dahmann et al., 2005; Kotov, 1997; Delaurentis et al., 2007; Baldwin and Sauser, 2009; Sauser et al., 2008; DeLaurentis and Crossley, 2005; Sahin, 2007a; Keating, et al. 2003; Shain et al. 2007b; Shenhar, 1994; Carlock and Fenton, 2001; Sage and Cuppon, 2001; Bar-Yam, 2004; Gorod et al. 2007; Jamshidi, 2008; Maier, 1994; Dagli and Ergin, 2008; Lane and Valerdi, 2007; Eisner, 1993; Keating, 2005; Pei, 2000; Crossley, 2004; Maier, 2005)

Holism (657 coded contents)

The main idea of holism is to focus on holistic language and solutions to capture the non-technical as well as technical aspects of complex problem domains. This holistic view provides a new systemic paradigm to achieve compatibility among multiple perspectives and to meet the challenges imposed by the surrounding environment, context, complexity, uncertainty, and dynamic nature of large complex systems. The idea is endorse the creation of "wholeness".

Cross references (Delaurentis et al. 2007; Maier, 1998; Keating et al. 2008; Hitchins, 2003; McCarter and White, 2008; Wells and Sage, 2009; Checkland, 1993; Bar-Yam, 2004, Gorod et al. 2007; Jamshidi, 2008; Maier, 1994; Dagli and Ergin, 2008; Lane and Valerdi, 2007; Eisner, 1993; Sage and Cuppon, 2001; Chen and Clothier, 2003; Bar-Yam, 2004; Gorod et al. 2008; Jamshidi, 2005; Maier, 1994; Lane and Boehm, 2008; Lane et al. 2010; Keating, 2005; Pei, 2000; Crossley, 2004; Maier, 2005)

SECOND STEP IN PHASE II APPLYING THE SYSTEMS THINKING CHARACTERISTICS TO INDIVIDUALS

Grounded theory coding and Nvivo software (QRS International version 10, 2014) were used to analyze the 550 different sources and derive the set of Sc characteristics. After providing a representative definition for each of the 7 core codes of the systems thinking characteristics, the researcher applied the systems thinking characteristics at the individual level. The set of systems thinking characteristics is essential to enable individuals to effectively deal with complex problem domains, which have typically been described as being consistent with the domain of SoS. These Sc characteristics capture and test the individuals' capacity for thinking consistent with engaging complex problem domains. This capacity determination is a unique contribution of the research since no single study described or mentioned such characteristics. As such, there is no 'reference' point against which the study or products can be contrasted.

Since the derived systems thinking characteristics emerged from system theory, complex systems/SoS, systems engineering, and systems thinking literature, some abstractions had to be made so that the characteristics could be applied at the individual level. Thus, the researcher has created the application table (Table 3.10) that is based on the most coded systems thinking characteristics and their comprehensive definitions (Figure 3.15). Systems thinking characteristics serve as a foundation for dealing with complex system environments. Essentially, they help individuals meet the challenges of understanding complex problems domains.

Applying interconnectivity (Sc1) at the individual level

In complex problems domains, individuals are called upon to understand both the assemblage of systems which constitute SoS and the way these systems are integrated to contribute to the overall mission. They must be able to identify the scope of the integration and clearly understand that the purpose of integration is to produce new behaviors and unique capabilities not feasible in any individual system. An individual should have an active role in orchestrating and working across heterogeneous systems involving people and technology within large systems. This integration will undoubtedly produce unforeseen consequences and risk behaviors that cause noise to the overall system performance. Thus, individuals should have the ability to provide input to mitigate these risks and identify areas where changes need to be considered. The heterogeneity and the multidimensionality of complex system problems requires individuals to possess interdisciplinary knowledge while still being specialists in one field.

The ensemble of systems need to interact, communicate, and collaborate among each other to obtain successful overall performance. The role of individuals within the systems is to closely observe these interactions and try to understand them from a holistic perspective. Individuals must coordinate and work as a team, communicate so that data and information is shared, and work closely with people and experts in other systems and with each other to achieve the overall goal of the complex system. To attain efficient communication, individuals should agree on a common language or jargon. The dynamic interaction with one or more systems and within the environment imposes difficulties in attaining an optimal solution to a problem. Individuals must, therefore, consider a range of satisficing (good enough) solutions in a dynamic environment. Often large complex systems' interactions and interdependencies are dynamic, uncertain, and nonlinear. The role of the individual is to treat the problem as a whole unit and avoid 'cause and effect' thinking paradigm.

Applying autonomy (Sc2) at the individual level

The ensemble of systems within complex systems are managed and operated independently. The role of individuals within SoS should value autonomy and retain it but still recognize the difficulties autonomy brings to complex systems and be able to balance the tension between autonomy and integration. When individual systems integrate, they sacrifice some degree of freedom in order to achieve the overall purpose of the system; therefore, individuals should know how to bargain and negotiate toward SoS objectives such that autonomy is preserved to the greatest extent possible while the behavior/performance of the overall system is preserved. This provides the basis for identifying where and how much sacrifice is needed for integration. In addition individuals need to be aware that these constituent systems if detached from SoS can fulfill their own purposes.

Applying evolutionary development (Sc3) at the individual level

The individual systems that compose large complex systems evolve in a rapid fashion, so the individual must pay close attention to the ongoing change in needs (requirements), technology and social infrastructure. The life cycle of large complex systems is continuous, iterative and evolves over time. Individuals should avoid adopting sequential traditional solutions and instead focus on the whole. Successful individuals in complex problems appreciate the diversity of multiple perspectives and are aware that these perspectives might bring dialog and understanding or confusion and misunderstanding. Individuals should be capable of exploring and prioritizing the numerous perspectives that have a direct impact on understanding complex problems. To maintain sustainability and viability in large complex systems, individuals must be keen observers of their surroundings and look for new opportunities to meet the challenges presented by the rapidly changing environment inherent in large complex systems.

Individuals must also be willing to accommodate any modifications or changes in the system due to the evolutionary nature and turbulent environment of large complex systems, and they should be able to distinguish between the needs for the SoS and the aggregate need of individual constituent systems. Individuals should understand the impact of these changes so that they can intervene to develop strategies and address problems.

Applying emergence (Sc4) at the individual level

The integration of multiple systems produces unintended behaviors/patterns. Even though these behaviors cannot be anticipated, individuals should be able to identify and look for all aspects of the problem including managerial, technical, human, political and others. In addition, they have to scan the environment and look for opportunities to exploit emergence. Individuals need to be aware that these emergent behaviors cannot reside uniquely in any of the constituent systems and therefore cannot be completely known in advance of system operation or attributed directly to individual components (subsystems) of a larger integrated system. Emergence provides the basis for treating complex systems problems as a whole unit.

Individuals should be capable of tracking and monitoring changes to minimize uncertainty and ambiguity. Since most, if not all, large complex systems operate in turbulent environments with fluid boundaries, individuals must avoid narrowing a problem too early. Successful individuals must appreciate the role flexibility plays in dealing with unintended behaviors and prepare for emergence by designing flexibility into the system. To identify a system's functions, behaviors, and emergence, individuals are required to think in a holistic way and avoid focusing on details. Holistic thinking helps one tolerate uncertainty and ambiguity in a turbulent environment.

Applying complexity (Sc5) at the individual level

Emergence, evolutionary development, dynamic interaction, integration of multiple systems, multiple perspectives, uncertainty, and contextual issues all lead to complexity in large complex problems. Individuals need to appreciate and assess the degree of complexity and realize that there is no full control and complete knowledge in complex systems environments. To alleviate the confusion, individuals should be able to identify and address the external influences that constrain the solution and the deployment of the solution, and they must pay close attention to the pace and evolution of the managerial, human/cultural, and related policy aspects of the problem. Another role to lessen the complexity is to observe the surrounding working environment.

Because SoS is a relatively new field, there are few accepted methodologies; therefore, individuals must align and map the nature of the problem, the methodology taken, and the surrounding context. Large complex systems deal with sociotechnical, ill-structured problems, thus individuals must focus on the non-technical as well as technical dimensions of the problem. The nature of large complex systems requires individuals to develop rapidly shifting solutions and make decisions across many aspects (i.e. culture, human/social).

Applying holism (Sc6) at the individual level

The complex nature of systems requires individuals to move beyond the reductionist based "cause and effect" paradigm to a more systemic paradigm based on holism. This new paradigm helps individuals to identify and assess all aspects of a problem by focusing on the whole and understanding that the whole cannot be accomplished by reduction. Individuals must be capable of seeing the big picture, understanding the system as a whole unit, and realizing that operating on the tiny details in the problem, without regard to the larger nature of interactions, might worsen overall system performance. This holistic perspective can provide the basis for allocating resources and seeing the big picture. In addition, focus on the whole can provide a glimpse into the relationships among systems, subsystems and their parts which is necessary for the selection, prioritization and screening of the relevant dimensions of the problem. A holistic systems-based view is important when assessing potential disruption to the complex problem domain from either internal or external forces.

Applying flexibility (Sc7) at the individual level

To successfully perform within a complex problem domain, individuals must be able to accommodate modifications and changes in the system. Individuals should know that adaptability is considered a main response to effectively deal with emergence. It is important for individuals to recognize that the design for complex systems must be flexible enough to add, adjust and/or remove any of the systems' components. Individuals effectively dealing with complexity must consider flexibility to be a positive force to withstand the challenges imposed by fluctuations in environmental conditions.

Table 3.10 and Figure 3.21 provide a succinct summary of the application process.

Table 3.10: Applying the Sc Characteristics at the Individual Level

Systems Thinking Characteristics (7-Sc)	Application Process
Interconnectivity	• Identify and understand the purpose of integration. • Be able to orchestrate and work across heterogeneous systems (i.e. people and culture). • Provide inputs to identify new risk behaviors and areas where changes need to be considered. • Pay close attention to the interactions and interdependencies among the systems from a holistic viewpoint. • Possess interdisciplinary knowledge. • Coordinate (teamwork), communicate (sharing data and information), and work closely (with other heterogeneous systems) to achieve the overall purpose.
Autonomy	• Understand the difficulties autonomy imposes on the complex problem domain. • Balance the tension between autonomy and integration. • Possess the ability to bargain and negotiate to address conflicting perspectives and objectives in complex systems.
Evolutionary Development	• Trace and map the ongoing change in needs, technology, and social infrastructure. • Focus on the whole system instead of the sequential traditional treatments (life cycle). • Take relevant multiple perspectives into consideration. • Explore the surrounding environment and look for new-outside opportunities to deal with the fast-paced growth of complex systems.

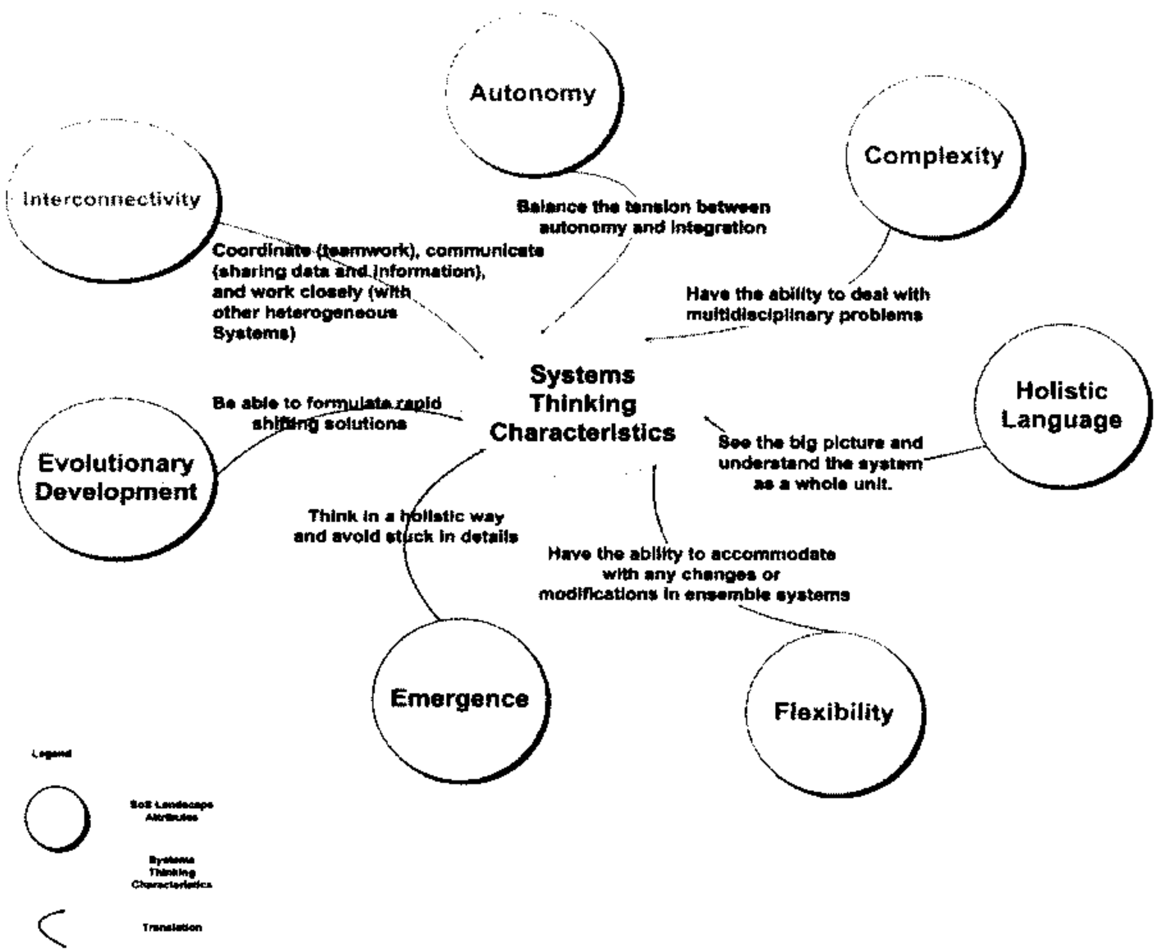
Table 3.10: Continued

Emergence	• Identify and inspect all aspects (non-technical) of the problem. • Explore the surrounding environment to deal with emergence. • Think in a holistic way and avoid overemphasis of details. • Prepare by designing for flexibility and adaptability in the system. • Avoid pursuit of optimal solutions and consider a range of satisficing solutions.
Complexity	• Appreciate and assess the degree of complexity (no full control) • Have the ability to distinguish the characteristics of complex system problems and understand the limitations of reductionist based approaches. • Identify and address the external influences that constrain the complex problem domain. • Establish an alignment between the nature of the problem, the methodology taken, and context where complex systems operate. • Grasp multidisciplinary problems.
Holism	• Recognize holism as an appropriate paradigm of thinking for complex systems and problems. • Identify and assess multiple aspects of the problem (e.g. technical, organizational, social, and political). • See the big picture and understand the system as a whole unit. • Focus on the whole and avoid looking at the reductionist details. • Demonstrate understanding of the relevant laws and principles appropriate to the problem under consideration.

Table 3.10: Continued

[redacted]

Figure 3.21: Application of Sc Characteristics at the Individual Level



PHASE III: THE DEVELOPMENT AND DEPLOYMENT OF A NON-DOMAIN SYSTEMS THINKING INSTRUMENT

After deriving the set of systems thinking characteristics in phase I and applying the set of systems thinking characteristics to individuals in phase II, this third phase was pursued to:

> *develop a non-domain specific systems thinking instrument which would capture the state of systems thinking at the individual level and indicate the predisposition for effectively engaging in the complex problem domain.*

This new systems thinking instrument assesses an individual's capacity to deal effectively with complex problems that would benefit from systems thinking, independent of specific domain knowledge, skills, or abilities. The outcome of the systems thinking instrument is an individual's profile detailing the systems thinking characteristics he/she possesses to effectively deal with the complex system problems prevalent in many fields including industry, the military, healthcare, etc. The systems thinking instrument helps to evaluate the correlation between systems thinking profiles and suitability for successful performance as a professional in a complex problem domain. Chapter V explores the three fold application of the systems thinking instrument across theoretical, methodological, and practical dimensions.

In effect, the instrument indicates the degree to which an individual's particular systems worldview is compatible with the complexity, uncertainty, ambiguity, and emergence inherent in the complex problem domain (Figure 3.15). The systems thinking instrument is designed to be a non-domain specific tool for the following reasons:

1. The few current tools related to systems thinking that are available are designed for small scale application within a specific setting or domain such as education. Thus there is a need to have a non-domain specific tool for systems thinking.
2. Systems thinking and system theory are applicable to a broad range of domains (Checkland, 1993; Von Bertalanffy, 1968; Clemson, 1984). Systems thinking in conjunction with system theory laws and principles provides the foundation upon which the systems thinking instrument is built.
3. There is a need for individuals to obtain systems skills (systems thinking characteristics) to deal with complex problems across many domains.
4. The development of the systems thinking instrument stems from the complex system attributes presented in Figure 3.15. A combination of these attributes is always present in complex system domain problems.
5. To build a non-domain specific instrument, the sample of the study was heterogeneous including participants of different backgrounds, education and experience.

For the purpose of developing the research instrument, a study sample was collected and a complex problem domain scenario was designed with 39 binary questions. The set of seven systems thinking characteristics was assessed through administration of the 39 binary questions (Appendix B &C for the survey instrument questions).

THE DESIGN OF THE COMPLEX PROBLEM DOMAIN SCENARIO

The literature has a rich array of scenario development techniques such as Schwartz's (1991) the Art of Long View; Van der Heijden's (1996) the Art of Strategic Conversation; Bradfield et al. (2005); Van Notten et al. (2003). Bishop et al. (2007) To review the techniques for developing scenarios, a review across some dominant literature in the field found eight categories of techniques with 23 variations used to develop scenarios. Below are these techniques and variations:

Judgment

Judgment which concerns how people see and predict the future without any methodological support is the first category for scenario development. Even though this category relies mainly on judgment, there are three primary techniques associated with it:

- Genius forecasting, developed by Kahn (1962), "encourages people to think the unthinkable" (p.11).
- Role playing such as war games is a form of group judgment.
- Coates (2000) developed a straightforward form of judgment. The steps start with identifying the domain and end with four scenarios.

Expected Future

The expected future category, unlike the judgment category, provides only one main scenario. Most of the "expected future" does not appear in its full form. The technique used in this category is "Trend Extrapolation". The aim of this technique is to study the current trends and patterns and extrapolate their effects into the future

(Judgment or mathematical techniques). Bishop et al. (2007) have identified two main variations related to trend extrapolation:

- Mona technique (Schultz, 1993): this technique elaborates the expected future scenario using future techniques.
- Systemic scenario: this technique adjusts the expected future scenario by giving the occurrence of potential future events.

Elaboration of Fixed Scenarios

The majority of scenario techniques develop scenarios from the very beginning, but this category "begins with scenarios that are decided ahead of time." [Bishop et al. (2007), p.12). There are two techniques associated with this category:

- Incasting which uses a historically based scenario to project to the future.
- The SRI Matrix, developed by Stanford Research Institute (SRI), starts with four fixed scenarios, namely expected future, the worst case, the best case, and the highly different alternatives.

Event Sequences

This category relies mainly on the past as sequences of events. One, two, or more events can occur in the future. Two variations were developed in this category:

- Probability Tree uses the tree branches to create scenario themes.
- Divergence Mapping, developed by Harman (1976), builds sequences that form the events of scenarios.

Backcasting

This category differs from the Genius Judgment technique in that it does not use judgmental processes to predict the future. Robinson, (1990) developed this technique by connecting the past to the present and the present to the potential future. Three techniques were developed for this category:

- The Horizon Mission methodology was developed by NASA, Impact of Future technique was developed by IBM Corporation, and Future Mapping was developed by Mason (2003). All these techniques share similarity in utilizing the same backward technique.

Dimensions of Uncertainty

This category was primarily developed to deal with the chaos and uncertainty in complex systems. There are three techniques associated with this category:

- GBN Matrix relies on two dimensions of uncertainty. "The four cells represent alternatively the four combinations of the poles of the two uncertainties" [Bishop et al. (2007), p.14].
- Morphologic analysis is a sub set of GBN matrix.
- MORPHOL Program is a computer program specified to measure and manage the complexity of morphologic analysis.

Cross impact analysis and Modeling

These are the last two categories in the scenario techniques.

The complex system scenario developed in this research is based on some characteristics of Schwartz's (1991) scenario development and the scenario typology of Van Notten et al. (2003). Van Notten et al. (2003) developed a framework that contains necessary elements to characterize scenarios. Below are the three main steps used in developing the complex system scenario:

First: Define the objective of the scenario

The purpose of this scenario is to explore how the proposed set of systems thinking characteristics can be examined to classify an individual's level of systemic thinking in relationship to complex problem domains.

Second: Gather the data

Scenario analysis uses expert opinion as an input rather than historical data. In the development of this scenario, the researcher identified the key factor to be examined by the scenario, which is whether the systems thinking instrument can measure what it is intended to measure, namely the systems thinking characteristics.

Third: Develop the scenario

One main scenario is developed. The reason for developing only one scenario is to avoid hitting diminishing returns by "overexamination" of any of the systems thinking characteristics.

The complex system scenario that was developed provides a description and background of a complex company. The questions following the scenario are general in nature and only intended to assess the individual thinking about any complex situation, such as this scenario. Below is the developed scenario:

You are a member of a large scale export management company that ships a variety of goods and services worldwide. The company was established over 30 years ago with one geographic location and one primary product. Over the years, the company has acquired several smaller companies to expand the product offerings, customer base, and global presence. The different units of the company are part of a larger system but remain geographically separated and operate somewhat autonomously, with separate operations, management, and performance goals. Product performance and customer expectations have generally been exceeded at the individual unit level.

THE SYSTEMS THINKING INSTRUMENT QUESTIONS

After deriving the set of systems thinking characteristics in phases I and II, 39 binary questions were established to test the set of systems thinking characteristics (7-Sc). Each systems thinking characteristic was tested using approximately 7 questions. Inquisite (Web Survey System, Version 9, 2014) was used to create the survey-questionnaires online. The systems thinking instrument was used to collect and generate the data from the study sample. Below are two sample questions from the study (Appendix C contains the complete list of questions).

- To address system performance focus should be on
    a. Individual members of the system
    b. Interactions between members of the system
- Which is more important to preserve?
    a. Local autonomy
    b. Global integration

Chapter IV examines and tests the capability of the systems thinking instrument to capture an individual's predisposition for systems thinking. The system thinking instrument is designed to provide better understanding of an individual's capacity to effectively deal with complex problem domains.

SAMPLE STUDY

"Sampling is the process of selecting units (such as people or organizations) from a population of interest so that by studying the sample you can fairly generalize your results to the population from which the units were chosen." [Trochim, (2001), p.41] To have tenable and generalizable research, researchers must select a population of interest and study it by selecting a representative sample. According to Trochim, (2001) there are two ways for generalization, proximal similarity and sampling model. The proximal similarity model begins by determining different generalizability contexts then chooses the best context that suits the study. The sampling model starts by identifying the population under study and then draws the sample from the selected population. If the sample gets generalized then automatically the population will be generalized. This research used the sampling model to generalize the selected sample. To ensure a concrete and coherent external validity, a nonprobability sampling procedure was used to draw the sample.

As mentioned, the systems thinking instrument is designed to be non-domain specific because systems skills are required in any domain. The population of interest for this research is individuals who engage and deal with complex problem domains. The sample for the study was heterogeneous and included participants from different backgrounds, educational levels and experience.

A nonprobability sampling approach, specifically the convenience sample, was used in this research. It is a convenience sample because individuals voluntarily participated in the research and not because it is easy to recruit. In this type of research it is hard to reach a population (all individuals who deal with complex problems across several domains). Therefore it is almost impossible to obtain a response rate. The researcher believes that probability sample is not appropriate for this kind of research since the systems thinking instrument is not developed for a specific context or domain. Thus, the sample consisted of graduate and undergraduate students from different universities and colleges, faculty members, managers, engineers, leaders, individuals, federal agencies and others. Chapter IV presents the demographics of the sample in details. The rationale for selecting a heterogeneous sample:

1. The idea of the systems thinking instrument is that it be generalizable beyond the selected sample to include larger applications of complex problem domains.
2. Since demographic factors such as, gender, race, educational level, etc. are not considered in the data analysis, the size of the selected sample could be increased to more than two hundred and forty participants. The larger the sample, the less the standard error.
3. The associated knowledge, skills, and abilities of the current participants have no impact on the sample framing. The purpose of the research is not to develop a personality profile, but rather to capture the state of systems thinking at the individual level to deal with complex problem domains.

4. The research used inductive approach to derive the system thinking characteristics and document that the set of systems thinking characteristics is the central phenomenon within a given sample.

Using nonprobability sampling there is no way to calculate the response rate. More than two hundred and forty individuals participated in this research phase. An invitation letter has been sent via e-mail to invite individuals from different domains to participate in the research endeavor and upon their indicating a willingness to participate, a web-link with instructions was sent via e-mail to participant.

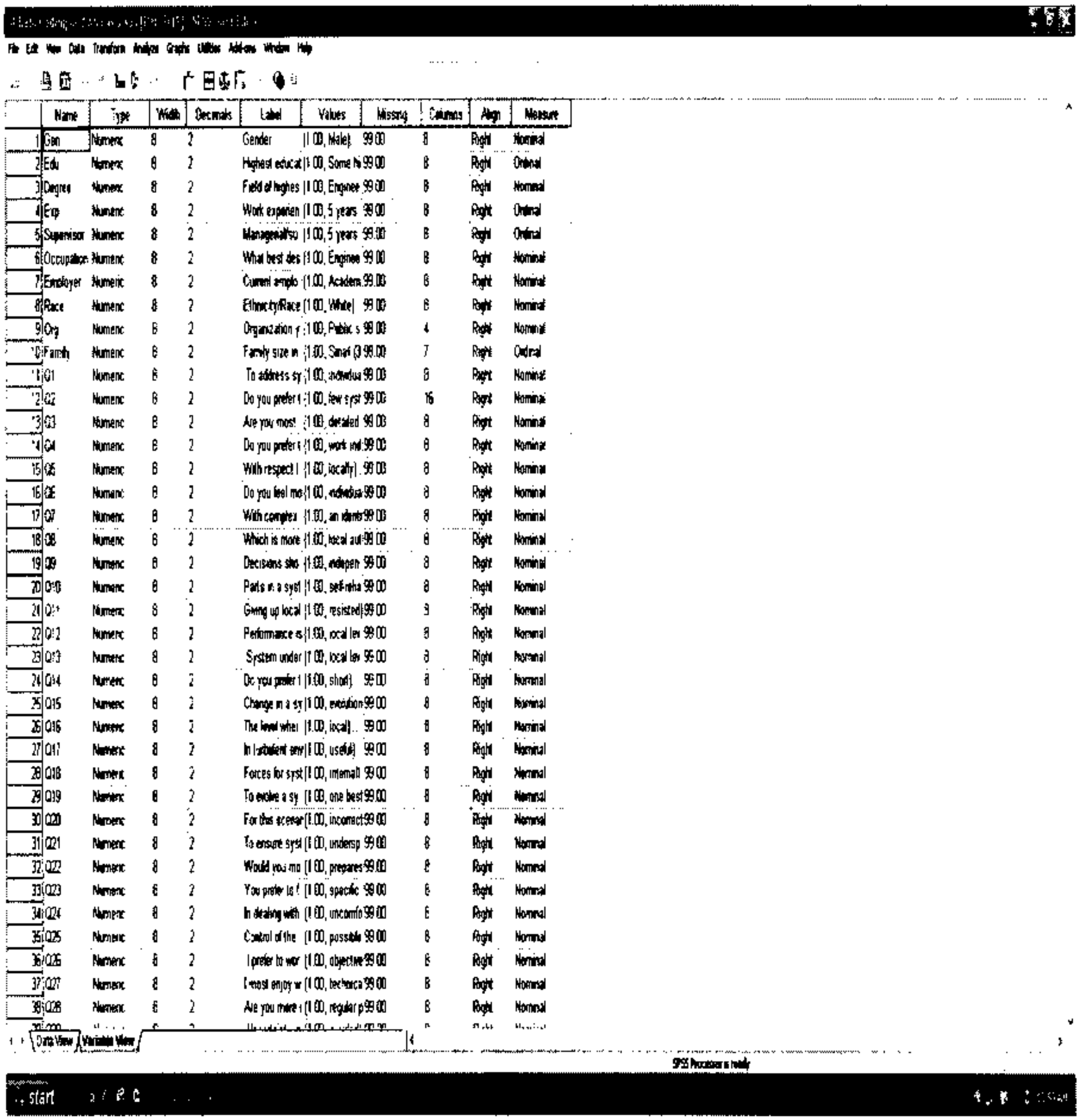
DATA COLLECTION

There are many methods and techniques to collect data. The type of method or technique depends primarily on the type of research (qualitative, quantitative, and mixed methods) (Creswell, 2008; Gibbs, 2007; Trochim, 2000).

In this research the systems thinking survey instrument was used to collect data for the instrument testing phase of the research. Primary data for the research was collected in two phases. In the first phase data was collected from the 55 participants who took part in the pilot test. The purpose of the pilot test was to reduce the systematic and random errors in the instrument and to gather feedback and suggestions from experts in the field. The data collected in the second phase was obtained from the individuals who participated in the actual research. In this phase a significant amount of data was collected but was not yet analyzed. The collected data consisted of two forms: nominal where order is not important and ordinal where natural order is important.

The researcher used SPSS statistical software to prepare this mass of data for analysis. A coding procedure was used to replace the answers with numbers so that it could be quantitatively analyzed (chapter IV). Figure 3.22 is a snapshot of the coding procedure.

Figure 3.22: Coding Procedure



	Name	Type	Width	Decimals	Label	Values	Missing	Columns	Align	Measure
1	Gen	Numeric	8	2	Gender	{1.00, Male}...	99.00	8	Right	Nominal
2	Edu	Numeric	8	2	Highest educat	{1.00, Some hi	99.00	8	Right	Ordinal
3	Degree	Numeric	8	2	Field of highes	{1.00, Enginee	99.00	8	Right	Nominal
4	Exp	Numeric	8	2	Work experien	{1.00, 5 years	99.00	8	Right	Ordinal
5	Supervisor	Numeric	8	2	Managerial/su	{1.00, 5 years	99.00	8	Right	Ordinal
6	Occupation	Numeric	8	2	What best des	{1.00, Enginee	99.00	8	Right	Nominal
7	Employer	Numeric	8	2	Current emplo	{1.00, Academ	99.00	8	Right	Nominal
8	Race	Numeric	8	2	Ethnicity/Race	{1.00, White}...	99.00	8	Right	Nominal
9	Org	Numeric	8	2	Organization r	{1.00, Public s	99.00	4	Right	Nominal
10	Family	Numeric	8	2	Family size in	{1.00, Small (3	99.00	7	Right	Ordinal
11	Q1	Numeric	8	2	To address sy	{1.00, individua	99.00	8	Right	Nominal
12	Q2	Numeric	8	2	Do you prefer t	{1.00, few syst	99.00	16	Right	Nominal
13	Q3	Numeric	8	2	Are you most	{1.00, detailed	99.00	8	Right	Nominal
14	Q4	Numeric	8	2	Do you prefer t	{1.00, work ind	99.00	8	Right	Nominal
15	Q5	Numeric	8	2	With respect t	{1.00, locally}...	99.00	8	Right	Nominal
16	Q6	Numeric	8	2	Do you feel mo	{1.00, individua	99.00	8	Right	Nominal
17	Q7	Numeric	8	2	With complex	{1.00, an identi	99.00	8	Right	Nominal
18	Q8	Numeric	8	2	Which is more	{1.00, local aut	99.00	8	Right	Nominal
19	Q9	Numeric	8	2	Decisions sho	{1.00, indepen	99.00	8	Right	Nominal
20	Q10	Numeric	8	2	Parts in a syst	{1.00, self-reha	99.00	8	Right	Nominal
21	Q11	Numeric	8	2	Giving up local	{1.00, resisted}	99.00	8	Right	Nominal
22	Q12	Numeric	8	2	Performance is	{1.00, local lev	99.00	8	Right	Nominal
23	Q13	Numeric	8	2	System under	{1.00, local lev	99.00	8	Right	Nominal
24	Q14	Numeric	8	2	Do you prefer t	{1.00, short}...	99.00	8	Right	Nominal
25	Q15	Numeric	8	2	Change in a sy	{1.00, evolution	99.00	8	Right	Nominal
26	Q16	Numeric	8	2	The level whe	{1.00, local}...	99.00	8	Right	Nominal
27	Q17	Numeric	8	2	In turbulent env	{1.00, useful}	99.00	8	Right	Nominal
28	Q18	Numeric	8	2	Forces for syst	{1.00, internal}	99.00	8	Right	Nominal
29	Q19	Numeric	8	2	To evolve a sy	{1.00, one best	99.00	8	Right	Nominal
30	Q20	Numeric	8	2	For this scenar	{1.00, incorrect	99.00	8	Right	Nominal
31	Q21	Numeric	8	2	To ensure syst	{1.00, undersp	99.00	8	Right	Nominal
32	Q22	Numeric	8	2	Would you mo	{1.00, prepares	99.00	8	Right	Nominal
33	Q23	Numeric	8	2	You prefer to f	{1.00, specific	99.00	8	Right	Nominal
34	Q24	Numeric	8	2	In dealing with	{1.00, uncomfo	99.00	8	Right	Nominal
35	Q25	Numeric	8	2	Control of the	{1.00, possible	99.00	8	Right	Nominal
36	Q26	Numeric	8	2	I prefer to wor	{1.00, objective	99.00	8	Right	Nominal
37	Q27	Numeric	8	2	I most enjoy w	{1.00, technica	99.00	8	Right	Nominal
38	Q28	Numeric	8	2	Are you more i	{1.00, regular p	99.00	8	Right	Nominal

After collecting the primary data, a statistical analysis technique (factor analysis) and Monte Carlo simulation were used to analyze and interpret the results of the research which are presented in Chapter IV. Table 3.11 illustrates the interaction with the participants.

Table 3.11: Participants Procedure

Data Collection	Description	Interaction with participants
Purpose	Test the hypothesis of the research.	Establish the external and internal validity of the systems thinking instrument.
Method	Systems thinking instrument.	1. An invitation letter has been sent via e-mail to invite individuals from different domains to participate in the research endeavor. 2. Upon their indicating a willingness to participate, a web-link with instructions was sent via e-mail to participants. 3. Participants took systems thinking questionnaires with approximately 15 min duration. 4. A number was used to code the response for each participant to the survey instrument. There is no identifying information that can link the participant to their response. 5. As discussed in chapter IV the results of the data analysis was anonymous without traceability to any participant.

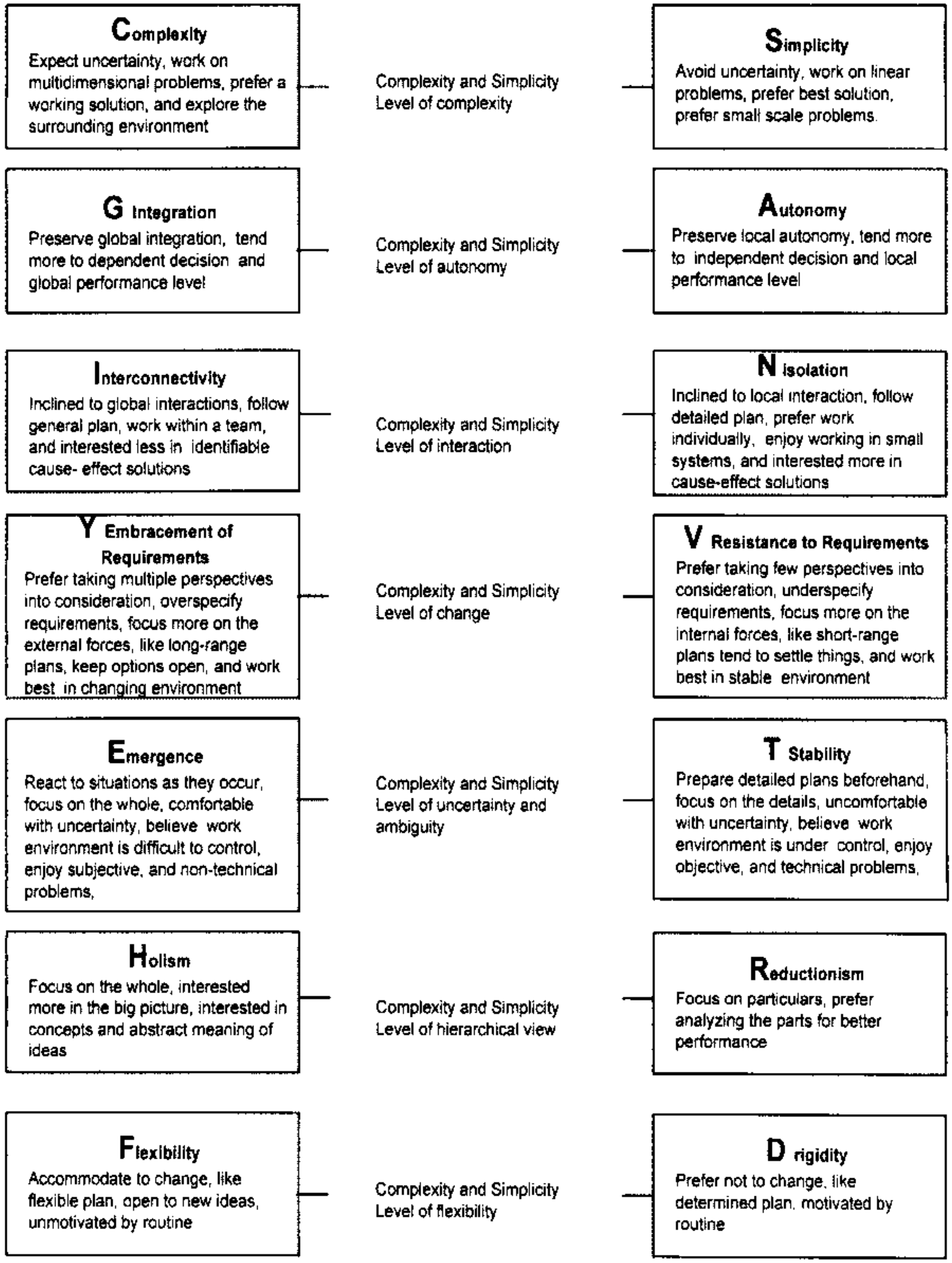
HOW THE SYSTEMS THINKING INSTRUMENT WORKS

The systems thinking instrument is comprised of 39 binary questions and is designed to provide a better understanding of an individual's capacity to effectively deal with complex problem domains. The Sc instrument consists of fourteen scored scales to measure the following seven preferences:

- C= Complexity OR S= Simplicity
- G= Integration OR A= Autonomy
- I=Interconnectivity OR N= Isolation
- H= Holism OR R= Reductionism
- E= Emergence OR T= Stability
- F= Flexibility OR D= Rigidity
- V= Embracement of requirements OR Y= Resistance to requirements

These fourteen labels reflect an individual's level of systems thinking in dealing with complex system problems. There are no intrinsically good or bad combinations; it depends solely on the uniqueness of the problem domain the individual is engaged in. During the pilot test, some participants felt that both answers could be correct within the same question. Figure 3.23 examines the preferences for each characteristic. As illustrated, an individual may prefer one characteristic over another or find that both characteristics within each pair are suitable. However, within each pair, (e.g. Holism or Reductionism) there is one that is agreed with the most or leaned toward more naturally. These systems characteristics (Sc) capture and test the individual's skills to engage complex problem domains.

Figure 3.23: Systems Thinking Characteristics Preferences Pairs



SCORING SHEET

Figure 3.24 below provides the scoring directions to obtain an individual's systems thinking profile.

Figure 3.24: Score Sheet

	a	b		a	b		a	b		a	b		a	b		a	b		a	b
1			7			12			18			24			21			35		
8			2			4			31			25			19			15		
3			20			14			9			37			32			26		
13			10			36			30			27			5			16		
33			11			38			22			28			34			6		
39						17			29			23								

Systems Thinking Profile

Directions for scoring

1- Add the total number of "a" answers in the box at the bottom of each column. Do the same for the "b" answers.

2- There are now seven pairs of numbers.

3- Circle the letter below the larger numbers of each pair.

4- These combinations identify the individual's systemic thinking profile in dealing with complex problems.

5- The complete profile is a combination of these fourteen letters.

WHAT IS AN INDIVIDUAL'S SYSTEMIC THINKING (Sc) TYPE

A good way to establish an individual framework to deal with complex problem domains is to take the Sc instrument. By taking this survey, a score will be provided, and this score will translate to an individual's level of systems thinking. As shown in Figure 3.23 there are seven levels of systems thinking with fourteen categories.

FIRST PAIR: COMPLEXITY Vs. SIMPLICITY

To illustrate, the first pair of preferences deals with the level of complexity. This level describes an individual's inclination to work in complex systems. Complexity and simplicity are notated as (C) for Complexity (S) for Simplicity.

If an individual is on the "complexity" spectrum (C), s/he probably: tends to accept working solutions, enjoys working on problems that have not only technological issues but also the inherent human/social, organizational/managerial, and political/policy dimensions, and expects and prepares for unexpected events.

In contrast, if an individual is on the "simplicity spectrum" (S), s/he probably: prefers to work on problems that have clear causes, prefers one best solution to the problem, and enjoys working on small scale problems

SECOND PAIR: AUTONOMY Vs. INTEGRATION

The second pair of preferences deals with the level of autonomy and describes an individual's comfort level in dealing with integration. Autonomy and integration are notated as (G) for integration or (A) autonomy.

An individual might find that s/he agrees with some of the attributes under the "autonomy" preference as well as with some attributes under "integration" preference. This could be quite true and natural. If an individual often leans toward making independent decisions, s/he still might tend to make dependent decisions in certain kinds of problems even though s/he actually prefers making independent decisions.

THIRD PAIR: INTERCONNECTIVITY Vs. ISOLATION

The third pair of preferences, which pertains to the level of interaction, describes the type of work environment an individual would prefer, either (I) Interconnectivity or (N) Isolation.

Some individuals might agree with every attribute related to the "interconnectivity" preference and agree little with "isolation". These individuals would probably lean more toward the "interconnectivity" preference indicating that they enjoy working on problems within a team and are less interested in clear identifiable cause-effect solutions. This does not mean that individuals who prefer to work individually on problems are wrong or somehow inferior; it only shows the different levels of systems thinking with respect to working in complex problem domains.

FOURTH PAIR: EMBRACEMENT OF REQUIREMENTS Vs. RESISTANCE

The fourth pair of preferences deals with level of change. This level describes an individual's inclination to make changes when dealing with complex problems. The preference pairs are notated as (Y) for embracement of requirements and (V) as resistance to requirements.

"Embracement of requirements" individuals prefer to work in changing environments while "resistance to requirements" individuals lean more toward stable environments. Some individuals are likely to consider multiple viewpoints before making a decision and others assume that these different perspectives could create distractions. Again there are no bad or good systems thinker types; it solely depends on the nature of the problem. If the problem has a large number of stakeholders, it is preferable to assign it to individuals who enjoy working in changing environments.

FIFTH PAIR: EMERGENCE Vs. STABILITY

The fifth pair of preferences deals with the level of uncertainty and ambiguity. This level describes an individual's preference to making decisions as (E) emergence or as (T) stability.

Individuals who agree with the emergence preference are more likely to focus more on the whole in solving problems instead of using a reductionist technique to focus on specific techniques. If individuals agree with half the "emergence" attributes and half the "stability" attributes, the way they choose to deal with problems is not as clear. To clarify again, there are no good or bad combinations; there are only variations from one individual to another. At this point at least, this research cannot tell if one combination is better than others.

SIXTH PAIR: HOLISM Vs. REDUCTIONISM

The sixth pair of preferences deals with the level of looking at the problem. This level describes an individual's inclination to looking at the problem in complex systems as (H) holism or as (R) reductionism. An individual whose answers fall into the (H) category is probably more interested in big picture concepts and ideas than his (R) counterpart who would prefer to focus on particulars and details. However, the nature of complex problems, their context and surrounding environment determine the way a problem should be managed. In some problems focusing on the parts is vital for determining the right –best solution, but for other problems this technique might worsen the overall performance of the system.

SEVENTH PAIR: FLEXIBILITY Vs. REGIDITY

The last pair of preferences deals with the level of flexibility. This level describes an individual's preference to making decisions as (F) Flexibility or as (D) rigidity.

An individual may find her/himself displaying attributes from both preferences with perhaps a clear predisposition toward the "emergence and complexity" preferences but also a slight tendency toward the "flexibility" preference.

SCENARIO EXAMPLE/PROFILE SHEET

Below is a description of a systems thinking profile sheet for an individual who participated in the survey. This profile sheet shows the individual's inclination for dealing with complex problem domains. This profile determines his level of systems thinking and indicates his predisposition to deal with complex problem domains.

The first pair of preferences (Interconnectivity vs Isolation), which pertains to the level of interaction, describes the type of work environment you prefer. Based on your score **(Interconnectivity 4, Isolation 2)** you:

- Enjoy working on problems within a team.

- Follow and apply a flexible plan.
- Are interested less in identifiable cause-effect solutions.
- Focus more on the overall interaction of the whole system.

The second pair of preferences (Autonomy vs Integration) deals with the level of autonomy. This level shows your comfort zone in dealing with integration of multiple systems. Based on your score (**Autonomy 3, Integration 2**), you:

- Lean more to independent decisions.
- Focus more on the local performance.
- Focus less on the overall performance of the system.

The third pair of preferences (Embracement over Requirements vs Resistance) deals with the level of change. This level describes your inclination to make changes in complex problems. Based on your score (**Resistance 1, Embracement of Requirements 5**) you:

- Prefer to work in changing and dynamic environments.
- Are apt to take multiple viewpoints into consideration before making a change or adjustment in the system.
- Focus on the internal and external forces such as contextual issues.
- Focus on obtaining a flexible design because you are aware of the shifting changes in system requirements.

The fourth pair of preferences (Emergence vs Stability) deals with the level of uncertainty and ambiguity. This level describes your preference in making decisions under uncertainty. Based on your score (**Emergence 4, Stabilty 2**) you:

- Apply a holistic view in understanding complex problems.
- Are comfortable dealing with uncertainty.
- Prefer working on non-technical problems.
- Follow a general-flexible plan to prepare for any unexpected behaviors.

The fifth pair of preferences (Complexity vs Simplicity) describes your inclination to working in complex problem domains. Based on your score (**Complexity 5, Simplicity 1**) you:

- Tend to accept working solutions.
- Enjoy working on problems that have not only technological issues but also the inherent human/social, organizational/managerial, and political/policy dimensions.
- Expect and prepare for unexpected events.
- Are willing to work in fast-changing environments.

The sixth pair of preferences (Holism vs Reductionism) deals with the level of hierarchical view of the system. This level describes your predisposition to look at the problem in complex systems. Based on your score (**Holism 3, Reductionism 2**) you:

- Focus more on the whole in solving problems.
- Formulate a problem by looking first at the big picture to understand the overall interaction.
- Focus more on the conceptual ideas instead of following details in cause-effect solutions.
- Focus more on the local performance.

The last pair of preferences (Flexibility vs Rigidity) deals with the level of flexibility. This level describes your preference in making adjustments. Based on your score (Flexibility 5, Rigidity 0) you:

- Enjoy working on multidimensional problems.
- React to problems as they occur.
- Avoid routine processes.
- Prepare flexible plans.

Overall your profile shows that your level of systems thinking is toward a more systemic (holistic) perspective.

SUMMARY

This chapter has shown the research design steps and the type of research design used by the researcher. A mixed method approach was used to collect and analyze qualitative and quantitative data, and grounded theory coding, which is an inductive research design, was used to derive the set of systems thinking characteristics. Following grounded theory as articulated by Strauss and Corbin (1990), a rigorous methodology was executed to inductively build the framework for systems thinking characteristics. Open coding, axial coding, and selective coding were procedures used to derive the set of systems thinking characteristics. Nvivo, a specialized software to support grounded theory, was used to navigate and manage the large amount of qualitative data for the research.

After deriving the set of systems thinking characteristics a systems thinking instrument was developed and successfully deployed to measure systems thinking characteristics for an individual given a complex problem domain scenario. More than two hundred and forty subjects participated in the research to test and validate the instrument. The outcome of the systems thinking instrument provides a profile that presents the systems thinking characteristics held by an individual. The chapter also has shown how this instrument works by explaining the 7 pairs of systems thinking preferences and the scoring directions.

CHAPTER IV

DATA ANALYSIS, RESULTS, AND INTERPRETATION

This chapter presents the results of the research and is divided into three sections. The first section, descriptive statistics, explores the patterns in the dataset. The second section presents the steps used in the factor analysis, and the third section describes the validity and reliability of the systems thinking instrument and demonstrates the different types of validity the researcher conducted to test the instrument.

DESCRIPTIVE STATISTICS

The first step in analyzing the dataset is to explore any patterns (Field, 2000).The survey instrument consists of ten demographic questions (Appendix C). The idea of the descriptive statistics is to gain information about the distribution of the sample and gain general views of the different characteristics of the sample structure. Table 4.1 shows the three measures of central tendency: mean, median, and mode and the three main measures of data variation: range, variance, and standard deviation. The formula used for calculating the arithmetic mean is

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Where **n**= the number of items being averaged (sample size)

$\bar{\mathbf{X}}$ = the mean

$\mathbf{X}_\mathbf{I}$= the value of each observation

$\sum$ = the sum of every observation in the equation

And the formula used for variance is

$$s^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1} = \frac{\sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}}{n-1} = \frac{\sum_{i=1}^{n} y_i^2 - n(\bar{y})^2}{n-1}$$

Where $\mathbf{S^2}$ = the variance

$\sum$ = the sum of every observation in the equation

$\mathbf{y_i}$ = every item in the observation set

$\bar{\mathbf{Y}}$ = the mean. The average of all the items (numbers) in the observation set.

n= the total number of observations (sample size)

Table 4.1: Descriptive Statistics

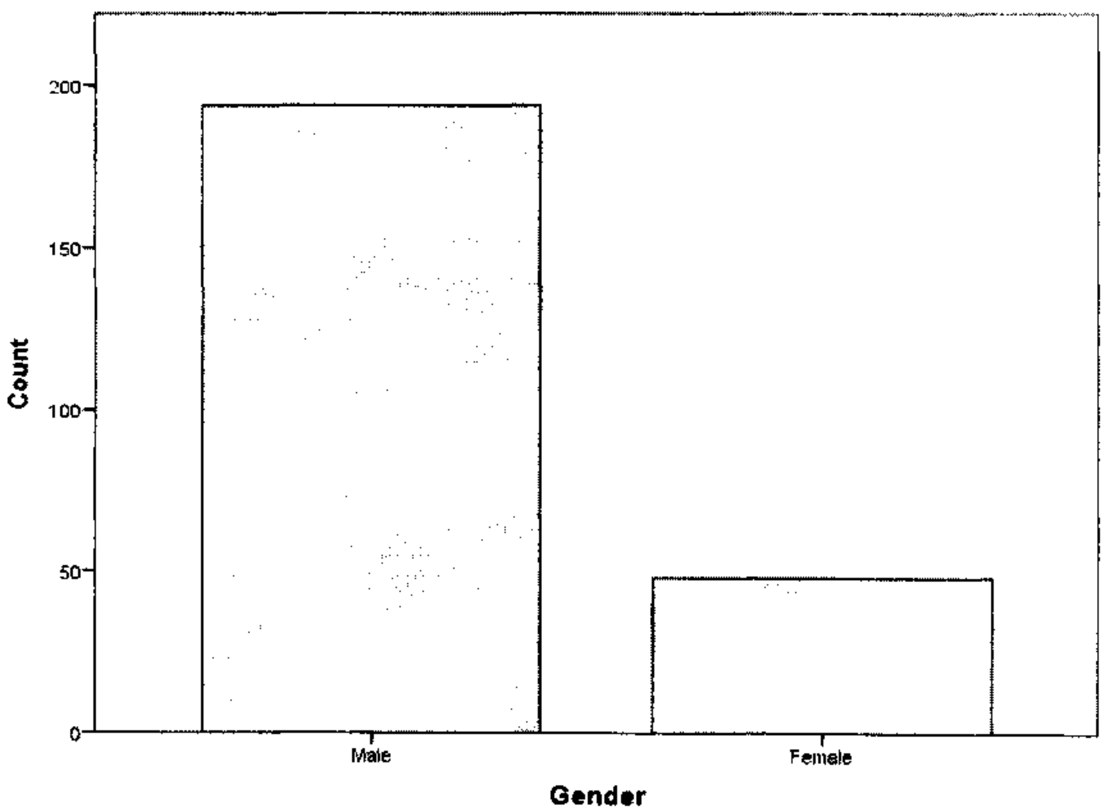
Demographics	**N**
Gender	242
Highest education level completed	242
Field of highest degree	242
Work experience	242
Managerial/supervisor experience	242
What best describes your current occupation	242
Current employer type	242
Ethnicity/Race	242
Valid N (listwise)	242

GRAPHS AND FIGURES

Graphs and figures are used to interpret and describe the patterns in the dataset. There are ten demographic questions in the survey instrument: (1) gender, (2) highest education level completed, (3) field of highest degree, (4) work experience, (5) managerial/supervisory experience, (6) current occupation, (7) current employer type, (8) ethnicity/race, (9) organization you work for, and (10) family size.

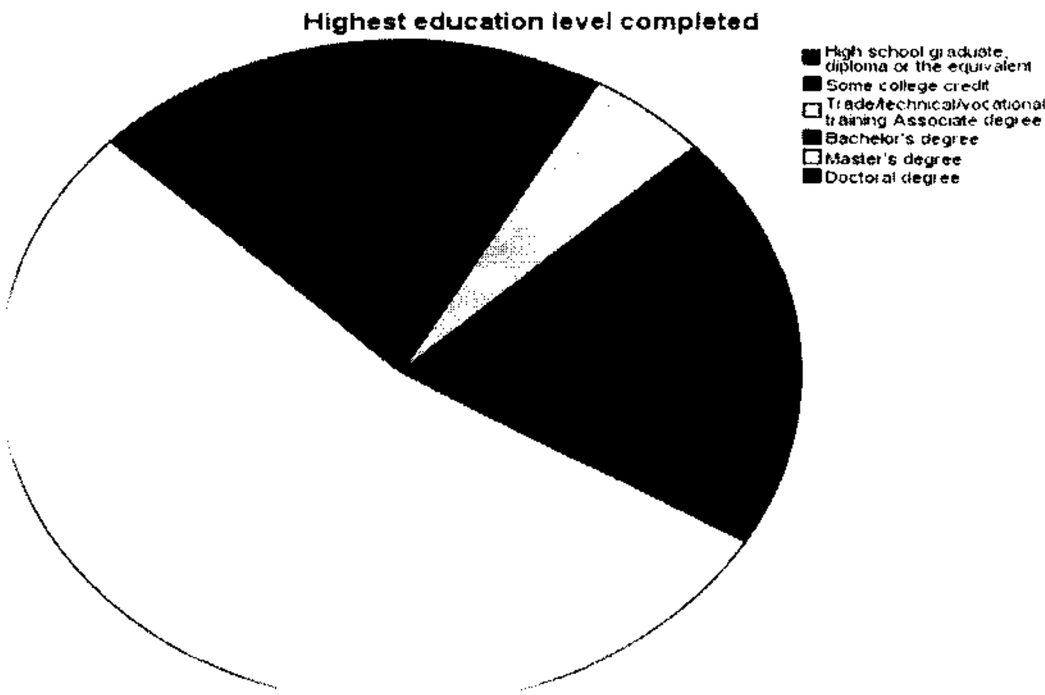
The simple bar chart (Figure 4.1) shows the distribution of males and females in the sample. The scale of the vertical axis reflects the number of males and females. The large column represents the number of males in the study.

Figure 4.1: Gender



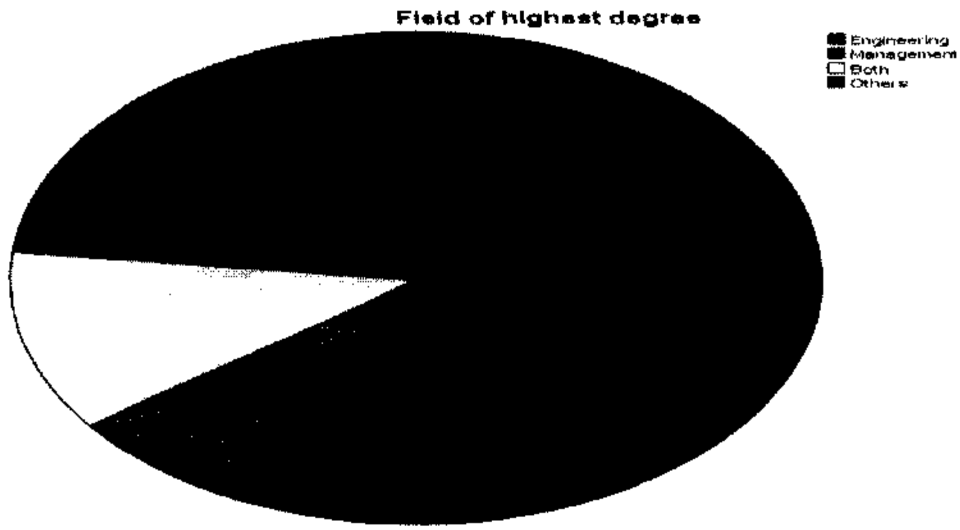
The pie chart (Figure 4.2) below exhibits the highest education degree of the participants. More than half of the participants have master's and doctoral degrees. Less than 25% of the participants have bachelor's degrees. A few participants have a diploma or the equivalent.

Figure 4.2: Highest Education Level Completed



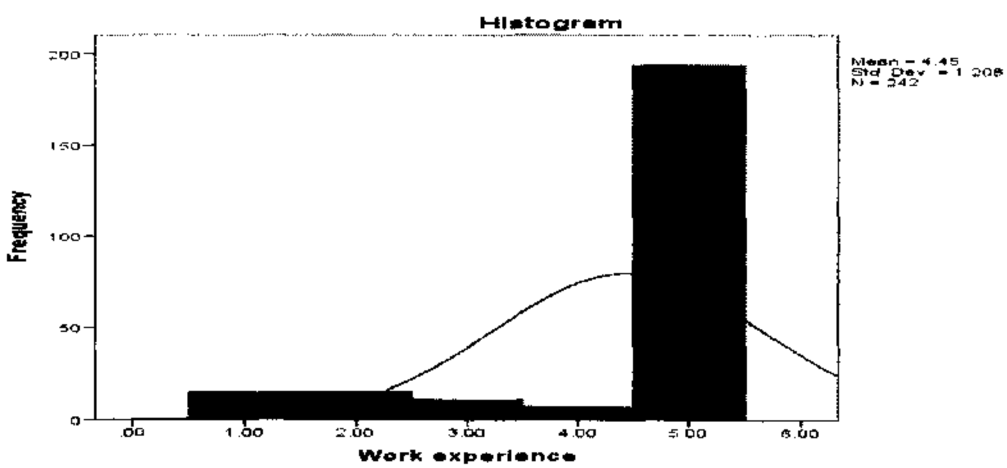
The pie chart in Figure 4.3 depicts the highest degree of participants by field. The pie is segregated into four fields: engineering, management, both, and others. Almost 40% of the participants have an engineering background, 25% a management background and approximately 20% a background in both engineering and management.

Figure 4.3: Field of Highest Degree



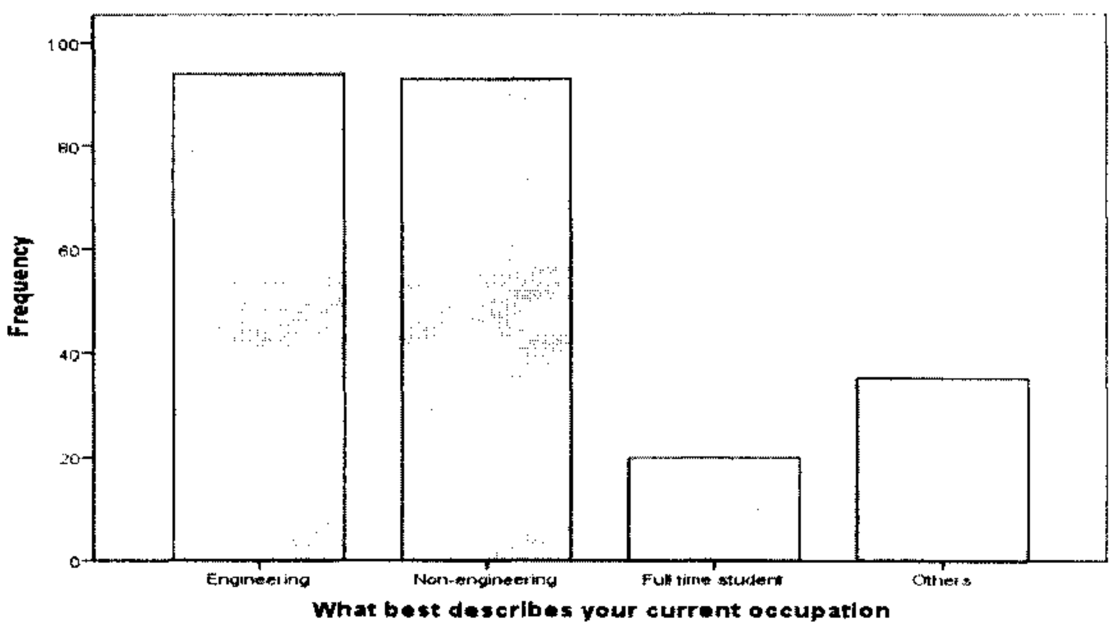
The histogram (Figure 4.4) illustrates the frequency of work experience. The highest of the bars are determined by the class frequency. As can be seen, most of the participants (around 190) have work experience of 21 years and above. The rest are within the (0-5), (6-10), (11-15), (16-20) categories.

Figure 4.4: Work Experience of the Participants



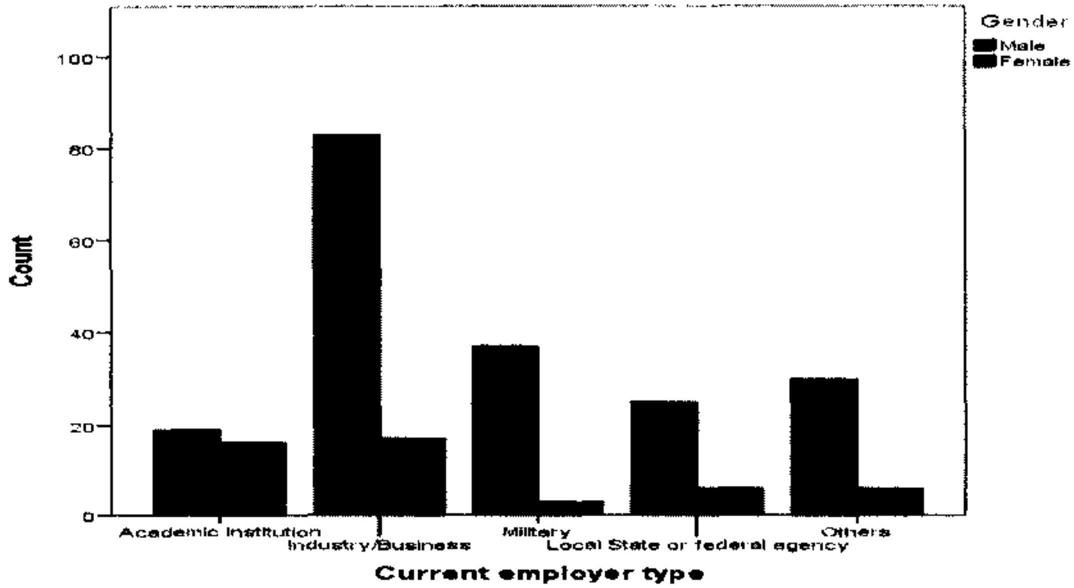
The bar chart (Figure 4.5) displays the current occupation of the participants. Around 90 participants work as engineers and almost the same number work as non-engineers. More than 20 are full time students.

Figure 4.5: Current Occupation of the Participants



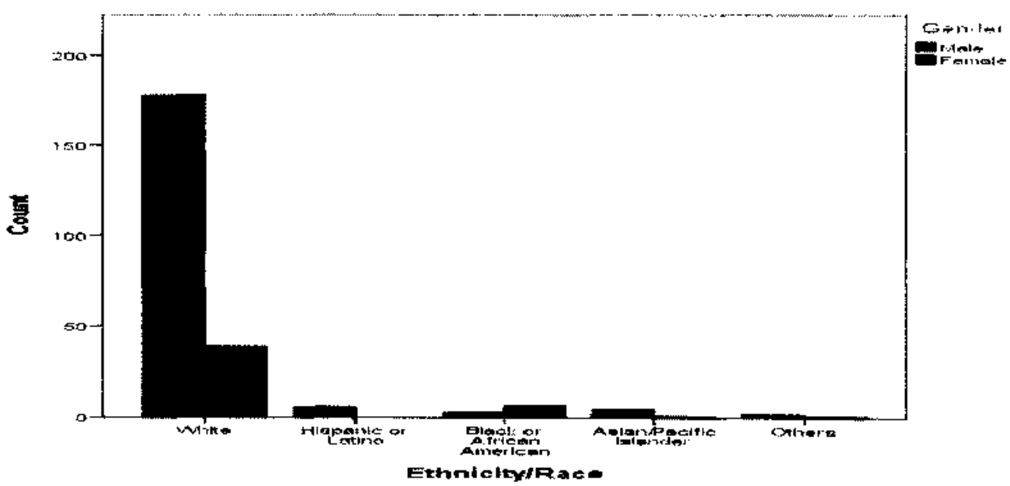
The clustered bar (Figure 4.6) shows the current employee type with respect to gender. Of the 242 participants, 85 males and 17 females are working in industry/business. The number of males and females employed in academic institutions is fairly close. The number of females in the military is low compared to the others.

Figure 4.6: Current Employer Type



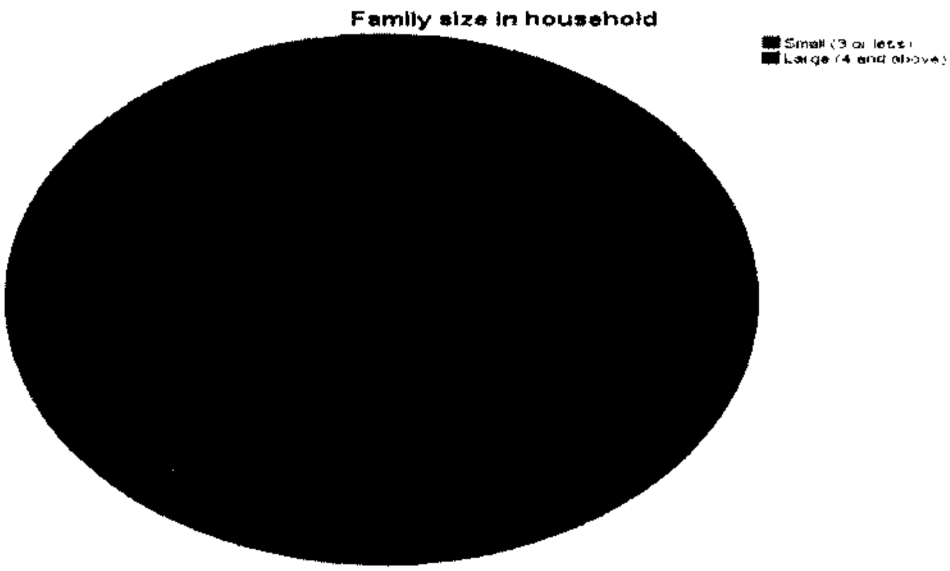
The clustered bar below (Figure 4.7) exhibits the ethnicity of the participants. There are five main categories: White, Hispanic, Black, Asian and others. As illustrated, of the 242 participants more than 200 are white where males constitute more than 150.

Figure 4.7: Ethnicity of the Participants



The chart (Figure 4.8) displays the family size of participants. Of the 242 participants almost 140 have a family with 4 members and above and approximately 102 participants with fewer than four members.

Figure 4.8: Family Size Household of the Participants



FACTOR ANALYSIS

Factor analysis has been widely used, especially in research that develops new instruments and techniques to measure a particular construct. There are different types of factor analysis, but the ones most often used are principle component analysis (PCA) and principle factor analysis (PFA.) Even though these are different techniques, they are very similar and are related to each other (Field, 2000; Rietveld and Van Hout, 1993). Factor analysis is a data reduction technique which takes a large set of variables and reduces them to a small set of factors (variables). Factor analysis ascertains if there are any strong correlations between the variables. The systems thinking instrument developed for this research consists of 44 questions and principle component analysis will reduce the redundancy among these questions.

The new systems thinking instrument will identify the level of systemic thinking of an individual to deal with complex problem domains. Principle component analysis (PCA) and Monte Carlo simulation are the techniques used to analyze and reduce the data and to check if the survey truly captures the level of systemic thinking. The main object of factor analysis is to reduce "the dimensionality of the original space and to give an interpretation to the new space, spanned by a reduced number of new dimensions which are supposed to underline the old ones" [Rietveld and Hout, (1993), p.254]. PCA provides a clear picture of the data and explores the variance among the variables. The purpose of factor analysis is to reduce a large number of variables into a manageable set of variables to truly measure the level of systems thinking. The following procedures are conducted to determine whether factors are important and to discover how to improve the systems thinking instrument.

1. KMO Test: measures sampling adequacy and the reliability of the results.
2. Anti-image correlation matrix: measures sampling adequacy.
3. Anti-image covariance matrix: measures sampling adequacy.
4. Communalities: explores the fitness of variables onto the factors.
5. Correlation matrix: any coefficients below .30 will be ignored.
6. Bartlett's Test of Sphericity: checks if the correlation matrix is an identity matrix or not.
7. Total variance explained: determines how many factors to retain.

8. Scree plot: checks for variance.

9. Monte Carlo simulation.

10. Unrotated component matrix: examines the loadings of variables.

11. Rotated component matrix: examines the loadings of variables after rotation.

12. Factor correlation matrix: shows the strength of the correlation between extracted factors.

The first three steps taken together measure the suitability of the sample for factor analysis and the rest of the steps will help determine validity and reliability for the new systems thinking instrument. When conducting principle component analysis, the first step is to code the data replacing the names with numbers so that it can be analyzed. Table 4.2 shows the questionnaire coding entry. The measurement of the variables in the dataset is either nominal (order is not important) or ordinal (natural order is important). All the measurements have an equal 8 width.

Table 4.2: Questionnaire Coding Entry

Name	Width	Label	Values	Measure
Gender	8	Gender	1.0 = Male 2.0 = Female	Nominal
Education	8	Education Level	1.0 = Some high level 2.0 = Diploma 3.0 = Some college credit 4.0 = Associate degree 5.0 = Bachelor's degree 6.0 = Master's degree 7.0 = Doctoral degree	Ordinal
Field	8	Field of Highest Degree	1.0 = Engineering 2.0 = Management 3.0 = Both 4.0 = Others	Nominal

Table 4.2: Continued

Experience	8	Work Experience	1.0= 5 years and below 2.0= 6-10 years 3.0= 11-15 years 4.0= 16-20 years 5.0= 21 years and above	Ordinal
Supervisor	8	Managerial Experience	1.0= 5 years and below 2.0= 6-10 years 3.0= 11-15 years 4.0= 16-20 years 5.0= 21 years and above	Ordinal
Occupation	8	Current Occupation	1.0= Engineering 2.0=Non-engineering 3.0=Full Time Student 4.0=Others	Nominal
Employer	8	Current Employer Type	1.0= Academic Institution 2.0=Industry/Business 3.0=Military 4.0=Local State 5.0=Others	Nominal
Race	8	Race	1.0= White 2.0=Hispanic 3.0=African American 4.0=Asian 5.0=Others	Nominal
Organization	8	Organization You Work For	1.0= Public Sector 2.0=Private Sector 3.0=Not-for-profit 4.0=Others	Nominal
Family	8	Family members in Household	1.0=Small (3 or less) 2.0= Large (4 and above)	Ordinal

NORMALITY SAMPLING ADEQUACY

To get reliable and generalizable results, the set of data should be appropriate for the use of factor analysis (Rietveld and Van Hout, 1993). To assess the suitability of the dataset to factor analysis, the following tests have been conducted using SPSS as statistical software.

KMO TEST

The starting point to determine if the data is appropriate for PCA is to check the sample size. The sample size should be considered well before the analysis begins because it seriously impacts the reliability of the analysis (Moore and McCable, 2001; Field, 2000; Habing, 2003). Field (2000) stated that "much has been written about the necessary sample size for factor analysis resulting in many rules-of-thumb" (p.443)

To make sure that the sample size is adequate for factor analysis, the Kaiser-Meyer-Olkin measure of sampling adequacy (KMO-test) is conducted (Table 4.4). If the value of the KMO-test is > 0.5 then the sample is adequate (Table 4.3). According to the KMO-test, the sample size in this research is considered to be well-suited with a score of 0.745. This score is an indicator of the possibility of generalizing the results beyond the collected sample. This test is considered a pre-check in the factor analysis procedure (George and Mallery, 2005). KMO-test values are always between 0 and 1, and the closer to 1 the better the value.

Table 4.3: KMO-Test Values

KMO-Test Values	Rule
< 0.5	Unacceptable
= 0.6	Acceptable
> 0.6	Adequate

Table 4.4: KMO-Test

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.745
Bartlett's Test of Sphericity	Approx. Chi-Square	1859.817
	Df	741
	Sig.	.000

ANTI-IMAGE CORRELATION MATRIX

To check for further sample size adequacy, in SPSS there is an option to calculate the anti-image matrix of covariance. "All elements on the diagonal of this matrix should be greater than 0.5 if the sample is adequate" [Field, (2000), p. 446]. As shown in Table 4.5, the diagonal values are all > 0.5 (0.71, 0.66, 0.71, 0.51, 0.834, 0.62, 0.54, 0.76, 0.67, 0.76). This means that factor analysis is sufficient and useful for the set of the data in this research. Table 4.5 illustrates only a sample of the 44 variables (See Appendix D for all values).

Table 4.5: Anti-Image Correlation Matrix Values

Anti-image Correlation	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Q1	[redacted]	-.050	-.067	-.012						
Q2	-.050	[redacted]	-.036	-.008						
Q3	-.067	-.036	[redacted]	-.051						
Q4	-.012	-.008	-.051	[redacted]						
A5	-.067	.037	.052	-.031	[redacted]					
Q6	.017	-.138	.062	-.233		[redacted]				
Q7	.024	-.034	-.021	-.078			[redacted]			
Q8	-.055	-.009	.061	-.097				[redacted]		
Q9	-.098	-.011	.004	.060					[redacted]	
Q10	.007	.026	-.011	.015						[redacted]

<u>ANTI-IMAGE COVARIANCE MATRIX</u>

The anti-image covariance matrix determines how good the factor model is by inspecting off-diagonal elements. The smaller the elements, the better the model. Table 4.6 shows a sample of these elements. In this research the factor model is considered ideal and reliable because:

1. The majority of the off-diagonal elements among the variables are relatively small <0.10, highlighted in green, and
2. All the diagonal variables are also > 0.5.

Table 4.6: Anti-Image Covariance Matrix Values

Anti-image Covariance	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Q1	**0.714**	-0.051	-0.062	-0.001	-0.068	0.012	0.014	-0.058	-0.091	0.006
Q2	-0.051	**0.665**	-0.038	-0.009	0.038	-0.137	-0.039	-0.004	-0.031	0.033
Q3	-0.062	-0.038	**0.723**	-0.059	0.042	0.064	-0.02	0.062	0.003	-0.008
Q4	-0.001	-0.009	-0.059	**0.518**	-0.028	-0.226	-0.08	-0.106	0.041	0.011
A5	-0.068	0.038	0.042	-0.028	**0.631**	-0.044	-0.032	-0.105	0.032	0.026
Q6	0.012	-0.137	0.064	-0.226	-0.044	**0.543**	0.068	0.028	-0.033	-0.081
Q7	0.014	-0.039	-0.02	-0.08	-0.032	0.068	**0.78**	0.006	-0.046	-0.02
Q8	-0.058	-0.004	0.062	-0.106	-0.105	0.028	0.006	**0.683**	-0.02	-0.076
Q9	-0.091	-0.031	0.003	0.041	0.032	-0.033	-0.046	-0.02	**0.768**	-0.151
Q10	0.006	0.033	-0.008	0.011	0.026	-0.081	-0.02	-0.076	-0.151	**0.763**

According to the Kaiser-Meyer-Olkin test and the readout of anti-image correlation and covariance matrixes, the dataset is well-suited for factor analysis. This confirms that (1) the results of the analysis are reliable, and (2) there is a high possibility of generalizing the results beyond the collected sample.

COMMUNALITIES

Communalities show how many variables might load on factors (Table 4.7). "If the communality of a variable is high, the extracted factors account for a big proportion of the variable's variance." [Kootstra, (2004), p.3] In other words the higher the communality of a variable, the more reliable the extracted factors and thus the better factor model. As can be seen from Table 4.7, there are two columns: the first one is conducted by the principle component analysis (PCA) and the second one is calculated by the factor analysis. The principle component analysis assumes that communalities are always 1, while factor analysis "does assume error variance" [Kootstra, (2004), p.4]. In factor analysis the communalities are estimated, which makes it more complicated than the principle component analysis (Field, 2000; Rietveld and Van Hout, 1993; Kootstra, 2004). Thus principle component analysis has been conducted in this research to estimate the extracted communalities.

As shown in Table 4.7 the extracted communalities of each variable, highlighted in red, are considered high. This indicates that:

1. All the variables (questions) are reflected well on the extracted factors and
2. There is a high possibility of generalizing the results of this research beyond the sample collected.

Even though there is a difference between factor analysis and principle component analysis, Rietveld and Van Hout, (1993) state that "the difference between factor analysis and principle component analysis decreased when the number of variables and the magnitudes of the factor loadings increased".(p.268). This extraction indicates the explained variance for each variable. Any value less than 0.3 would indicate that the variable does not fit well with the other items on each extracted factor. It is important to mention that Table 4.7 is just a sample of 24 variables (questions). However, of the 44 variables, 39 have extracted values >0.3.

Table 4.7: Sample of Communalities Values

Communalities	Initial	Extraction
To address system performance focus should be on	1.000	.549
Do you prefer to work with	1.000	.582
Are you most comfortable developing a	1.000	.593
Do you prefer to	1.000	.715
With respect to system interactions, at which level would you prefer to focus	1.000	.582
Do you feel more comfortable working	1.000	.673
With complex problems, there is usually	1.000	.621
Which is more important to preserve	1.000	.617
Decisions should be made	1.000	.589
Parts in a system should be more	1.000	.527
Giving up local decision, authority should be	1.000	.604
Performance is determined more by actions at the	1.000	.512
System understanding is more preferable at which level	1.000	.693
Do you prefer to think about the time to implement change in a system as	1.000	.612

Table 4.7: Continued

Communalities	**Initial**	**Extraction**
Change in a system is most likely to occur as	**1.000**	**.633**
The level where change in a system is best implemented is	**1.000**	**.625**
In turbulent environments, planning for system change is	**1.000**	**.638**
Forces for system change are driven more	**1.000**	**.508**
To evolve a system, would you prefer to find	**1.000**	**.663**
For this scenario, there are multiple perspectives that are	**1.000**	**.646**
To ensure system performance, it is better to	**1.000**	**.675**
Would you most prefer to work in a group that	**1.000**	**.639**
You prefer to focus more on the	**1.000**	**.691**
In dealing with unexpected changes, you are generally	**1.000**	**.631**

CORRELATION MATRIX

What follows the determination of communalities in component factor analysis is the establishment of the correlation matrix shown in Tables 4.8 and 4.9. The correlation matrix explores the intercorrelations between the variables (44 questions). The correlation matrix is a starting point before extracting the factors. It gives a clear idea about the combinations of intercorrelations among the variables (George and Mallery, 2003). High intercorrelations show the importance of a variable to a factor (Field, 2000). These correlations explain how the variables fall on a regression line. The 1's down the diagonal represent each variable correlated with itself and the matrix is symmetrical on the diagonal. If the p value of Bartlett's Test is ≤ 0.05, then the correlation is statistically significant. As can be seen from Table 4.8, any number highlighted in red means that the correlation is statistically significant. Since the intercorrelations among the variables are significant, PCA is appropriate for the dataset. Scanning through the values in the correlation matrix shows that there are several values ≥ 0.10, and these are highlighted in red.

Table 4.8: Sample of Correlation Matrix

Sample of Correlation Matrix	**To address system performance focus should be on**	**Do you prefer to work with**	**Are you most comfortable developing a**	**Do you prefer to**	**With respect to system interactions, at which level would you prefer to focus**	**Do you feel more comfortable working**	**With complex problems, there is usually**
To address system performance focus should be on	**1.000**	**.105**	.082	**.162**	**.209**	**.126**	.068
Do you prefer to work with	**.105**	**1.000**	.073	**.243**	**.190**	**.321**	.036
Are you most comfortable developing a	.082	.073	**1.000**	**.174**	.015	.028	**.110**
Do you prefer to	**.162**	**.243**	**.174**	**1.000**	**.300**	**.525**	**.157**
With respect to system interactions, at which level would you prefer	**.209**	**.190**	.015	**.300**	**1.000**	**.285**	.070

Table 4.8: Continued

Do you feel more comfortable working	**.126**	**.321**	.028	**.525**	**.285**	**1.000**	.020
With complex problems, there is usually	.068	.036	.110	**.157**	.070	.020	1.000
Which is more important to preserve	.177	.075	-.118	.181	.240	.091	-.007
Decisions should be made	.216	.078	.011	.063	.073	.089	.073
Parts in a system should be more	.085	.096	.064	.137	.100	.161	.066
You prefer to focus more on the	.139	.082	.317	.304	.225	.218	.065
Performance is determined more by actions at the	.056	.181	-.029	.129	.147	.008	-.018
To evolve a system, would you prefer to find	.108	.135	-.021	.144	.200	.100	.158

<u>THE BARTLETT'S TEST OF SPHERICITY</u>

The Bartlett's Test of Sphericity checks the intercorrelations between the variables (the correlation matrix Table). This test has to be significant. "The variables have to be intercorrelated, but they should not correlate too highly as this causes difficulty in determining the unique contribution of the variables to a factor." [Field (2000), p.444] For the test to be significant, the p value should be ≤ 0.05. Table 4.9 below shows that Bartlett's Test of Sphericity is significant which means that the variables are intercorrelated but not too highly. In addition, this test confirms the suitability of the dataset to the factor analysis with a Sig value of .000.

Table 4.9: Bartlett's Test

Bartlett's Test of Sphericity		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.723
Bartlett's Test of Sphericity	Approx. Chi-Square	2151.124
	df	946
	Sig.	.000

The values reflected in the correlation matrix and the Bartlett's Test of Sphericity have shown that the results obtained from the principle component analysis are highly reliable and tenable. A synopsis of the data shows:

1. The correlation matrix is not an identity matrix, which means that there is a scope for data reduction. If the correlation matrix is an identity matrix this explains that there are no correlations between the variables and PCA is not adequate.
2. There is no extreme multicollinearity between the variables. The multicollinearity causes disturbance and difficulties in extracting the factors.
3. The data set is well suited for this type of analysis.

FACTORS EXTRACTION

The systems thinking instrument measures the level of systems thinking of individuals. The idea is to cluster these 44 questions together into underlying factors which make it more manageable and reliable. The use of principle component analysis is to discover what the underlying factors might be within the data.

As explained in the preceding section (correlation matrix, and Bartlett's Test of Sphericity), the intercorrelations between variables describe the importance of a variable to a factor. The positive eigenvalues of the correlation matrix give an estimate of how many factors will be extracted. However, this could be misleading, "as it is possible to obtain eigenvalues that are positive but very close to zero." [Kootstra, (2004), p.6] To avoid this dilemma, (Field, 2000, p. 436; Rietveld and Van Hout, 1993, p. 274) suggested some rules with respect to factor extraction:

1. Keep the factors with large eigenvalues using Kaiser's criterion of retaining.
2. Retain the factors with a cumulative variance 60-80%.
3. Check the scree plot (elbow point).

There are other criteria that can be used for retaining factors such as Jolliffe's criterion that recommends retaining factors with eigenvalues larger than 0.7. However, the researcher used Kaiser's criterion because it is widely used in research.

TOTAL VARIANCE EXPLAINED (EXTRACTED FACTORS)

In this subsection the total variance is explained by the initial and extracted eigenvalues. Principle component analysis measures "the total amount of variations observed in all variables." [George and Mallery, (2003), p. 247] Based on the mentioned rules, a total variance explained table has been conducted (Table 4.10). According to Kaiser's criterion any value larger than 1 should be retained because it explains more variance than others.

The Total variance explained in Table 4.10 explores the underlying extracted factors. Table 4.10 below is divided into two sections. The first section represents the initial eigenvalues before extraction and the second section represents the sum of squared loadings. In section one, the first column shows the eigenvalues for each variable; column two and three respectively calculate the variance for each variable to the total variance of the variables as well as the cumulative variance. For example, the first factor accounted for 12.791% of the total variance and the cumulative variance for the second factor equals the sum of the variance for the first factor 12.791% and the second factor 18.855 % and so on.

The second section of Table 4.10 explores the extracted factors with column one identifying the total number of factors to be retained by calculating their eigenvalues. Based on Guttman-Kaiser criterion there are 16 factors with eigenvalues larger than 1 that need to be retained. Column two and three respectively explain the variance for each extracted factor and the cumulative percentage of variables within the extracted factors. This means that the first 16 factors explained 62.285% of variance in the original 44 variables. Table 4.11 shows the other variables with eigenvalues less than 1. These variables were not included further in the analysis.

Table 4.10: Total Variance Explained

Component	Initial Eigenvalues (section one)			Extraction Sums of Squared Loadings (section two)		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.628	12.791	12.791	5.628	12.791	12.791
2	2.668	6.064	18.855	2.668	6.064	18.855
3	2.122	4.822	23.677	2.122	4.822	23.677
4	1.929	4.383	28.060	1.929	4.383	28.060
5	1.551	3.525	31.585	1.551	3.525	31.585
6	1.479	3.362	34.947	1.479	3.362	34.947
7	1.396	3.172	38.119	1.396	3.172	38.119
8	1.342	3.049	41.168	1.342	3.049	41.168
9	1.295	2.942	44.111	1.295	2.942	44.111
10	1.257	2.858	46.968	1.257	2.858	46.968
11	1.218	2.768	49.737	1.218	2.768	49.737
12	1.204	2.737	52.473	1.204	2.737	52.473
13	1.163	2.643	55.116	1.163	2.643	55.116
14	1.097	2.493	57.609	1.097	2.493	57.609
15	1.056	2.401	60.010	1.056	2.401	60.010
16	1.001	2.274	62.284	1.001	2.274	62.284

Extraction Method: Principal Component Analysis.

Table 4.11: Variables with Eigenvalues less than 1

Total Variance Explained			
	Initial Eigenvalues		
Component	Total	% of Variance	Cumulative %
17	.982	2.232	64.516
18	.950	2.158	66.674
19	.880	1.999	68.674
20	.867	1.970	70.644
21	.815	1.853	72.497
22	.790	1.795	74.292
23	.781	1.775	76.066
24	.734	1.667	77.733
25	.714	1.623	79.356
26	.678	1.542	80.898
27	.658	1.496	82.394
28	.649	1.476	83.870
29	.606	1.378	85.248
30	.592	1.345	86.593
31	.561	1.275	87.868
32	.551	1.251	89.119
33	.514	1.168	90.288
34	.502	1.142	91.429
35	.482	1.097	92.526
36	.448	1.018	93.544
37	.423	.961	94.504
38	.414	.940	95.445
39	.403	.915	96.360
40	.384	.874	97.234
41	.337	.766	98.000
42	.310	.704	98.704
43	.293	.666	99.370
44	.277	.630	100.000
Extraction Method: Principal Component Analysis.			

These 16 factors are the fundamental constructs that describe the set of variables in this research. Looking at the total variance shown in Table 4.10, factor one is extracted based on the variables whose shared correlations "explain the greatest amount of the total variance." (12.791%) [George and Mallery, (2003), p. 247] Then factor two is extracted based on the greatest amount of the remaining variance and so on until "as many factors have been extracted as there are variables." The eigenvalues are arranged in a descending order in which the first eigenvalue for the first factor is 5.628 and the last eigenvalue for the last extracted factor is 1.001. After inspecting the total explained variance table, the researcher was able to determine the number of factors needed to represent the variables. In the initial eigenvalues, "there are as many factors as variables." As can be seen from both sections in Table 4.10, the cumulative variance in the initial eigenvalues (62.284) equals the cumulative variance in the extracted eigenvalues (62.284). This indicates that there is no loss (unexplained variation) in the total variance after extraction.

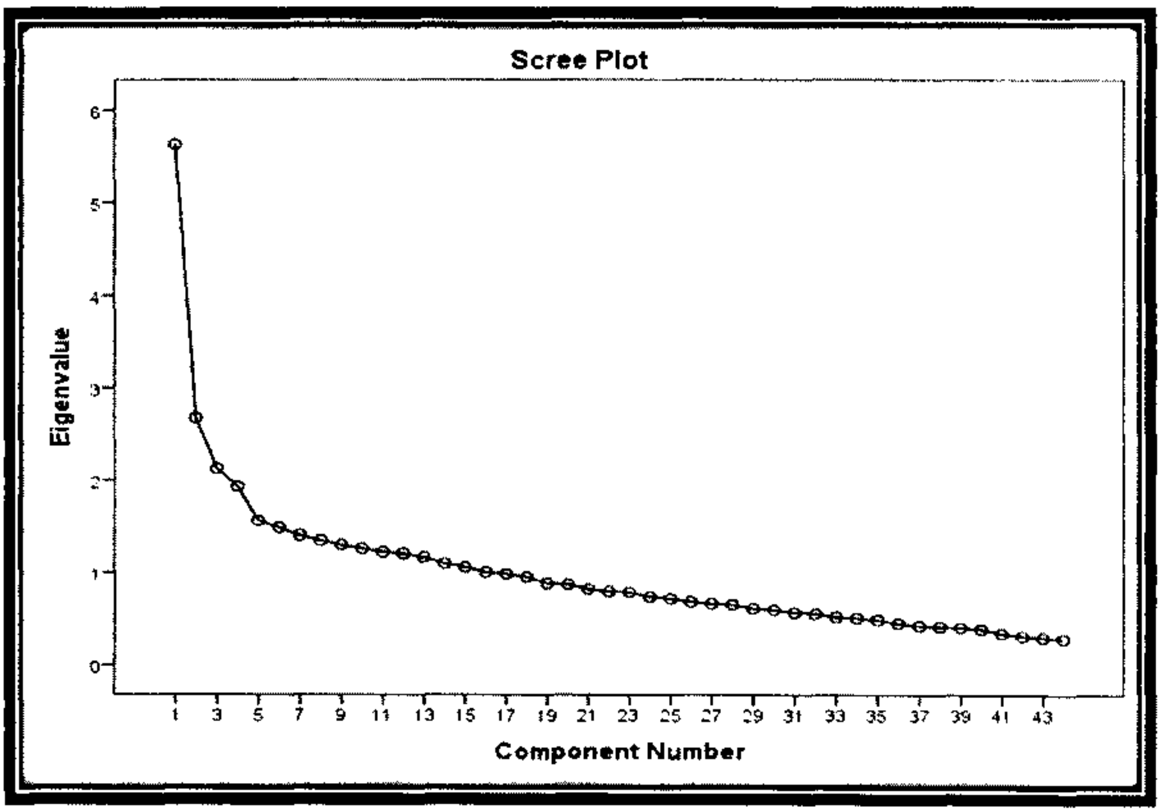
So far the researcher has met the first two rules by showing that the factors with large eigenvalues were retained and that the factors with a variance of 60-80% were also retained. The next subsection will describe how the third rule, the scree plot, was applied.

SCREE PLOT

The scree plot "plots the eigenvalues on a bicoordinate plane" [George and Mallery, (2003), p. 257] and is the last checkpoint for extraction. To determine the optimal extracted factors, this rule states that it is very important to retain all the factors before the breaking point or elbow (Field, 2000). In other words, all the factors on the steep slope should be retained and the other factors should be neglected. The rationale behind the scree plot is that the factors on the steep slope represent the greatest amount of variance in all the other factors. The factors after the breaking point do not add much to the final decision. Looking at the scree plot (Figure 4.9),

1. The researcher decided to retain the first 5 factors which are located on the steep slope,
2. The researcher found that these 5 factors capture much more of the variance than the other factors,
3. The researcher kept factor 5 for interpretation because it was just on the edge of the elbow, and
4. The researcher eliminated the remaining factors from the rotation as well as the interpretation.

Figure 4.9: Scree Plot Breaking Point



MONTE CARLO SIMULATION

To make sure that these 5 factors are the optimal factors to be included in the interpretation, the researcher used Monte Carlo Simulation to conduct parallel analysis. Monte Carlo Simulation is a useful double check technique. This kind of analysis cannot be obtained or run using SPSS. Comparing the eigenvalues in the total variance explained table with the eigenvalues generated from the simulation (Figure 4.11) is the last criterion to validate and determine the number of factors to be retained. To run the parallel analysis, the simulation requires three main variables (1) the total number of variables, (2) the total number of subjects, and (3) the number of replications. Based on these three variables, the simulation will generate a random set of eigenvalues and then compare them with the eigenvalues obtained from the dataset. In this research the number of variables is 44, the number of participants in the survey is 242, and the number of replications is 100. The simulation can run up to 1000 replications. The researcher ran different replications, and the eigenvalues were almost the same; thus 100 replications were sufficient for the parallel analysis. Recalling the extracted eigenvalues from the total variance explained table (Table 4.11), the researcher conducted a comparison analysis as shown in Figure 4.10.

Figure 4.10: Eigenvalues Comparison Analysis

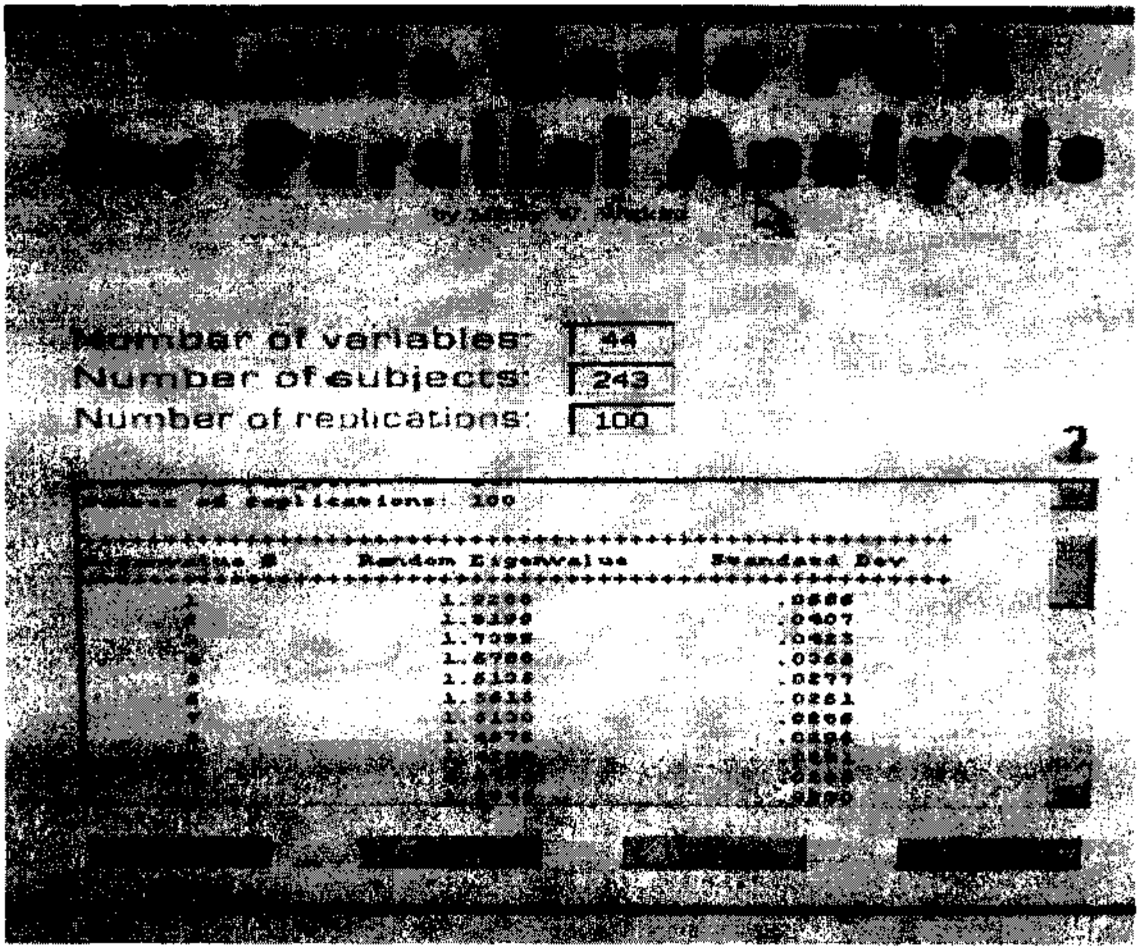
Factors	Total Variance Explained	Monte Carlo Simulation Parallel Analysis
1	5.337	1.9288
2	2.624	1.8199
3	1.942	1.7399
4	1.889	1.6768
5	1.522	1.6135
6	1.363	1.5615

It is essential to obtain the factors with eigenvalues greater than the random eigenvalues generated from the simulation. Thus, the researcher has retained the first 4 factors because their eigenvalues (total variance explained) are larger than the generated random eigenvalues from the parallel analysis. Even though the eigenvalue for the fifth factor is less than the criterion eigenvalue of the parallel analysis (1.522<1.6135), the researcher decided to retain this factor for three reasons:

1. The difference is close;
2. The breaking point (scree plot) was on the edge with factor five;
3. The researcher had good conceptual knowledge of the data set.

As can be seen from Figure 4.11 below, the remaining factors were rejected and excluded from the analysis.

Figure 4.11: Monte Carlo Parallel Analysis



FACTORS ROTATION AND INTERPRETATION

This section discusses how the validity of the systems thinking instrument is checked. Once factors have been extracted, the rotation process comes into place. This step is necessary to better interpret what each factor means. The rotation process indicates "the strength of relationship between a particular variable and a particular factor."

[George and Mallery, (2003), p. 248] The loadings values are between -1 and +1 (Field, 2000; George and Mallery, 2003; Comrey and Lee, 1992) If the variable loads high (> 0 .3) on one or two factors, this indicates a strong relationship. If the variable loads on all the extracted factors, this needs to be reconsidered. A variable with high reflection (loading) on a factor indicates the validity of this variable in measuring a specific construct. To obtain a good valid structure, variables need to

1. Load on one or two factors maximum and
2. Load with high values of loadings > 0.3.

There are two main types of rotations, namely orthogonal and oblique. The choice of the rotation is based on the dataset (Field, 2000). The researcher chose orthogonal rotation because it is not necessary to have a correlation between the extracted factors. The systems thinking instrument was designed in a way that certain questions (out of 44 questions) measure one characteristic and the second set of questions measure the second characteristic and so on until all together the 44 questions measure the seven characteristics. "The choice of rotation depends on whether there is a good theoretical reason to suppose that the factors should be related." [Field, (2000), p.439]

There are five methods to perform rotations: Varimax, Direct Oblimin, Quartimax, Equanmax, and Promax. The researcher used Varimax for orthogonal rotation. In order to establish the unrotated component matrix, rotated component matrix, and correlation matrix Varimax must be used.

UNROTATED COMPONENT MATRIX

The unrotated component matrix gives an idea about the unrotated variables' loadings on the extracted factors. It is quite difficult to make interpretations based on the eigenvalues of the extracted factors; therefore, unrotated and rotated component matrixes are explained. As mentioned in the previous section, the researcher has decided to retain five main factors which are the optimal solution for the dataset. "Factor rotation process alters the pattern of the factor loadings, and hence can improve interpretation." [Kootstra, (2004), p. 6]

Unrotated component matrix (Table 4.12) is a final step before rotating the factors. The purpose of this matrix is not to make a final decision, but rather to generate an idea about the unrotated loadings of the variables and how they might change after the rotation.

Table 4.12: Unrotated Component Matrix

Component Matrix[a]					
Instrument Questions (variables)	Component				
	1	2	3	4	5
Are you more inclined to work on something that follows	.602				
I prefer to work on problems for which the approach is	.567				
You prefer to focus more on the	.559				
In thinking about this company, I would prefer to focus on	.537	.303			
Do you prefer to	.532				
I am most comfortable working where circumstances require	-.507				
A system can be understood by analyzing the parts	.480			.433	
With respect to system interactions, at which level would you prefer to focus	.469	.374			
I prefer to work on problems for which the solution is	.458				

Table 4.12: Continued

I would describe my preferred work environment as one for which outcomes	.455		-.359		
Do you feel more comfortable working	.454			-.395	
To ensure system performance, it is better to	-.420				
With respect to execution of a plan	.417				
In dealing with a system, would you prefer it to be	.403	.336	.310		
Once successful, a technical solution will result in similar success in other applications	.381				
A solution to a problem should always be	.366			.356	
Do you prefer to work with	.357		.311	-.344	
Are you most comfortable developing a	.348				
Once a system is deployed, modifications and adjustments indicate that the design was	.348				
I most enjoy working on problems that primarily involve	.332				
Which is more important to preserve		.575			
Performance is determined more by actions at the		.465			
Giving up local decision, authority should be		.419			-.362
Control of the work environment is		-.411			-.311
Would you most prefer to work in a group that	.386	-.402			
Decisions should be made		.330			
To address system performance focus should be on	.320	.324	-.319		
Parts in a system should be more					
Change in a system is most likely to occur as			.509		
In planning for a system solution, plans should be			-.442		
In turbulent environments, planning for system change is		-.329	.426		
Do you prefer to think about the time to implement change in a system as			-.364		
System performance is primarily determined by individual components	.437			.523	
In solving a problem, I generally try to get opinions from				-.371	
In dealing with unexpected changes, you are generally	.342			-.355	
Forces for system change are driven more					.465
To evolve a system, would you prefer to	.332		-.355		.416

Table 4.12: Continued

A problem should first be addressed at what level					.413
Once desired performance is achieved, a system should be					-.399

As mentioned, researchers do not rely heavily on the component matrix, and the final decision is made based on the rotated component matrix (George and Mallery, 2003). However, the unrotated component matrix gives an idea about the importance of unrotated loadings. Review of this matrix indicates that:

1. Most of the unrotated loading values are larger than 30% which gives a substantive indicator that these variables are reliable but cannot say much until the rotated component matrix is interpreted.
2. All the variables are loaded on the extracted factors.

Since the unrotated component matrix is tenuous, the next step is to rotate the extracted factors.

ROTATED COMPONENT MATRIX

This is the last step in the analysis as well as the final decision of selecting the significant variables (with high loadings). As already reported this matrix is important for the interpretation of the extracted factors. Stevens in (1992) provides a table to determine what loading should be used for interpretation (as cited in Field, (2000), p.440). The researcher used this table, the most common one, as a gauge for gaining better interpretability of the extracted factors (Table 4.13).

Table 4.13: Loadings Significance

Sample Size	Loadings significance with α = 0.01
[illegible]	0.722
100	> 0.512
[illegible]	[illegible]
300	>0.298
[illegible]	[illegible]
1000	>0.162

as cited in Field, 2000, 440

To make the rotated component matrix (Table 4.14) readable and interpretable, there is an option in SPSS to sort the loadings based on the size and to suppress small coefficients that are less than 0.3. Thus the loading variables are arranged in a descending order for each factor. Based on Table 4.14 below, any loading value larger than > 0.3 is significant. This significance gives "indication of the substantive importance of a variable to a factor." [Field, (2000), p.441] Table 4.14 explores the rotated loadings for each variable on the extracted factors.

Table 4.14: Rotated Component Matrix

Rotated Component Matrix[a]					
Instrument Questions (Variables)	Component				
	1	2	3	4	5
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Would you most prefer to work in a group that	.542				
Control of the work environment is [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 4.14: Continued

I prefer to work on problems for which the approach is	.513				
[redacted]					
You prefer to focus more on the	.474				
[redacted]					
With respect to execution of a plan	.465				
[redacted]					
I am most comfortable working where circumstances require	.453	.393			
[redacted]					
Once successful, a technical solution will result in similar success in other applications	.321				
[redacted]					
In dealing with a system, would you prefer it to be		.632			
[redacted]					
With respect to system interactions, at which level would you prefer to focus		.580			
[redacted]					
In dealing with unexpected changes, you are generally		.465			
[redacted]					

Table 4.14: Continued

System performance is primarily determined by individual components	.334		.583		
[redacted]					
Which is more important to preserve			.499		
[redacted]					
In thinking about this company, I would prefer to focus on		.339	.465		
[redacted]					
Parts in a system should be more			.447		
[redacted]					
Performance is determined more by actions at the			.417		
[redacted]					
To evolve a system, would you prefer to find				.628	
[redacted]					
Once a system is deployed, modifications and adjustments indicate that the design was				.414	
[redacted]					
In turbulent environments, planning for system change is	.350				.537

Table 4.14: Continued

[redacted]					.490
Do you prefer to think about the time to implement change in a system as					.455
[redacted]					.425
A problem should first be addressed at what level					.393
[redacted]					
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.[a]					
[redacted]					

An initial look at these loadings indicates a "very good structure." The table shows how the 39 variables (questions) are reflected well (loaded) on the extracted factors. As discussed earlier, a valid-substantive structure consists of variables with high loading >0.3 and are reflected on one or two of the designated factors. Ideally it is better to have more than five variables (questions) loading on each factor (Stevens, 1992). Factor 1 has a total of 16 loadings, factor 2 has a total of 9 loadings, factor 3 has a total of 10 loadings, factor 4 with 8 loadings, and the last factor has 6 loadings. There are five variables with loadings value > 0.6, nine variables with loadings value > 0.5, twenty variables with loadings > 0.4, and finally five variables with loadings > 0.3. The variables (questions) that have one or two loadings onto factors indicate a strong relationship, which means that they truly measure the characteristics of systems thinking.

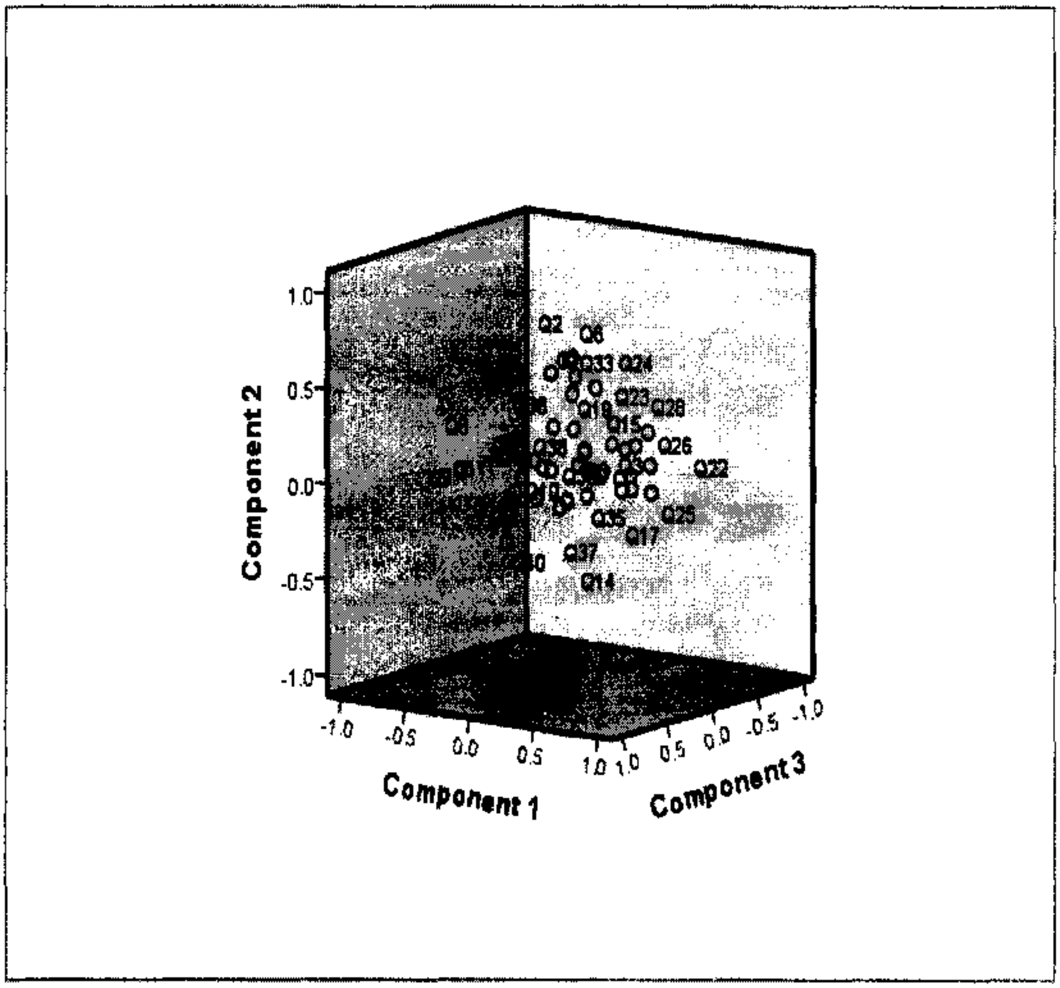
Interestingly, all the variables (questions) are loading on either one or two factors. This gives a clear indication of the validity and reliability of the systems thinking instrument.

The updated version of the survey instrument (Appendix C) consists of 39 questions to measure the level of systems thinking of individuals. There are 7 main characteristics that measure the level of systems thinking (Interconnectivity, Autonomy, Complexity, Evolutionary Development , Emergence, Holism, and Flexibility). Component factor analysis was conducted on the 44 questions to see if these characteristics truly measure what they are supposed to measure.

The next step in the interpretation was " to look at the content of questions that load onto the same factor to try to identify common themes." [Field, (2000), p.463] The questions with significant loadings onto the first factors are related to emergence and holism characteristics; therefore this factor is labeled *EME-HOLISM*. The questions with high loadings onto the second factor are pertinent to interconnectivity and complexity characteristics, so it is labeled *INTER-COMP*. The questions with high loadings onto the third factor are relevant to autonomy and holism characteristics and are therefore labeled *AUTO-HOLISM*. The eight questions that load onto the fourth factor are related to evolutionary development and flexibility characteristics and are labeled *EVO-FLEX*. The six questions that load onto the fifth factor are relevant to evolutionary development and holism and are labeled *EVO-HOLISM*. This reveals that the 39 questions have high loadings with excellent internal validity and appear to truly measure the level of systems thinking. Figure 4.12 illustrates how the first three extracted components rotated.

Figure 4.12: Rotation Plot

Component Plot in Rotated Space



FACTORS CORRELATION MATRIX

This is the last step in the component factor analysis (CFA). Table 4.15 investigates if there is a correlation between the extracted factors (Field, 2009). There is a low relationship between the factors. This verifies that these factors are not independent.

Table 4.15: Factors Correlation Matrix

Component Correlation Matrix					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	1.000	.242	.188	.298	.13
[illegible]	[illegible]	[illegible]000	.240	.144	.23
3	.188	.240	1.000	.123	.17
[illegible]	[illegible]	[illegible]	[illegible]	1.000	.14
5	.023	.093	.097	.081	1.000
[illegible] Principal [illegible] Analysis. [illegible] Rotation [illegible] Normalization. [illegible]					

Tables 4.16 and 4.17 below present the overview of the steps for the internal validity and reliability of the systems thinking instrument. Based on factor analysis 5 variables (questions) were omitted from the systems thinking instrument. A detailed discussion will be provided in the conclusion section of this chapter.

Table 4.16: Overview of the Steps (1-6)

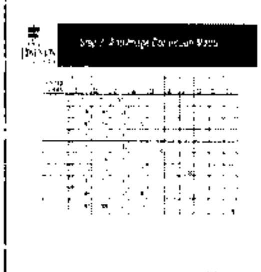
Steps	Approach	Contribution to the validity of the instrument	Requirements	Meet the requirements	Application (produces)
Step 1	KMO test	Measures sampling adequacy and the reliability of the results	Any value > 0.5 then the sample is adequate	KMO test for this research is 0.74 > 0.5	
Step 2	Anti-image correlation matrix	Measures sampling adequacy and determines if the dataset is appropriate for factor analysis	All elements on the diagonal of this matrix should be greater than 0.5	All the diagonal values are > 0.5	

Table 4.16: Continued

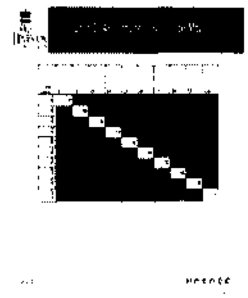
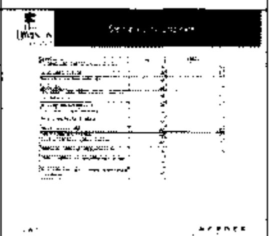
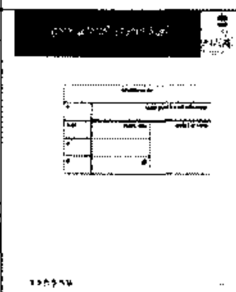
Step 3	Anti-image covariance matrix	Measures sampling adequacy and determines how good the factor model is	The smaller the off-diagonal elements, the better the model is	The majority of the off-diagonal elements are < 0.10	
Step 4	Communalities	Explores the fitness of the variables (questions) onto the factors	The higher the communality of a variable > 0.3, the more reliable the extracted factors	Of the 44 variables, 39 have extracted values > 0.5	
Step 5	Correlation matrix	Explores the intercorrelations between the variables (44 questions)	Intercorrelations among the variables should be ≥ 0.10	In this research the variables (questions) are statistically significant with values ≥ 0.10	
Step 6	The Bartlett's test of Sphericity	Checks the intercorrelations between the variables	The p value should be ≤ 0.05 (first check point of extraction)	In this research the p value is sig .000	

Table 4.17: Overview of the Steps (7-12)

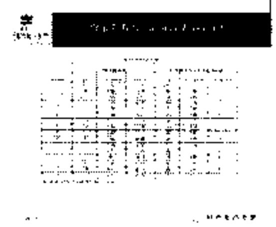
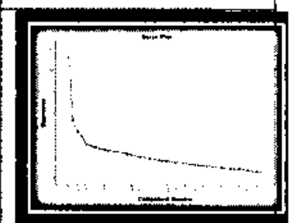
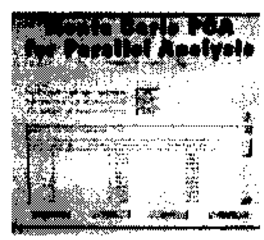
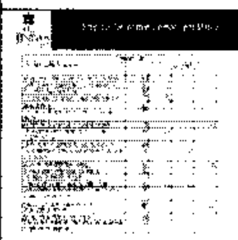
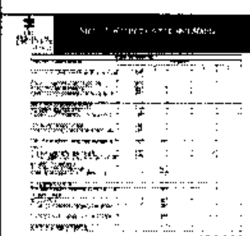
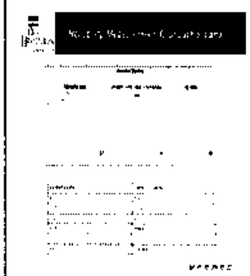
Steps	Approach	Contribution to the validity of the instrument	Requirements	Meet the requirements	Application (produces)
Step 7	Factors extraction (total variance explained)	Explores the underlying extracted factors (second check point of extraction)	Any eigenvalues larger > 1 should be retained because it explains more variance than others	16 factors > 1 are the fundamental constructs that describe the set of variables in this research	
Step 8	Scree Plot	Third checkpoint for factors extraction	Retain all the factors before the breaking point or elbow	The researcher decided to retain the first 5 factors which are located on the steep slope	
Step 9	Monte Carlo analysis	Last check point to validate and determine the number of factors to be retained	Make sure that these 5 factors are the optimal factors to be included in the interpretation	Comparing the eigenvalues in the total variance explained table with the eigenvalues generated from the simulation (5 factors obtained)	
Step 10	Unrotated component matrix	Gives an idea about the unrotated variables' loadings on the extracted factors	Generate an idea about the unrotated loadings of the variables and how they might change after the rotation	Most of the unrotated loading values are larger than 30%	
Step 11	Rotated component matrix	This is the last step in the analysis as well as the final decision of selecting the significant variables (with high loadings)	interpretation of the extracted factors	39 variables (questions) are reflected well (loaded) on the extracted factors	

Table 4.17: Continued

Step 12	Reliability of the survey instrument	Check the internal consistency of the survey instrument	The measure is reliable if the results are the same over and over	Chronbach's Alpha Test (α) and Parallel Test are obtained with very good reliability α 0.81	

HYPOTHESIS TEST AND RESEARCH QUESTIONS

Recalling Chapter I of the dissertation, the alternative hypothesis of this research is:

H_1: *there is a statistically significant relationship between the proposed SC characteristics and the state of systemic thinking at the individual level that would indicate predisposition for engaging in the complex problem domain.*

which was tested against the null hypothesis

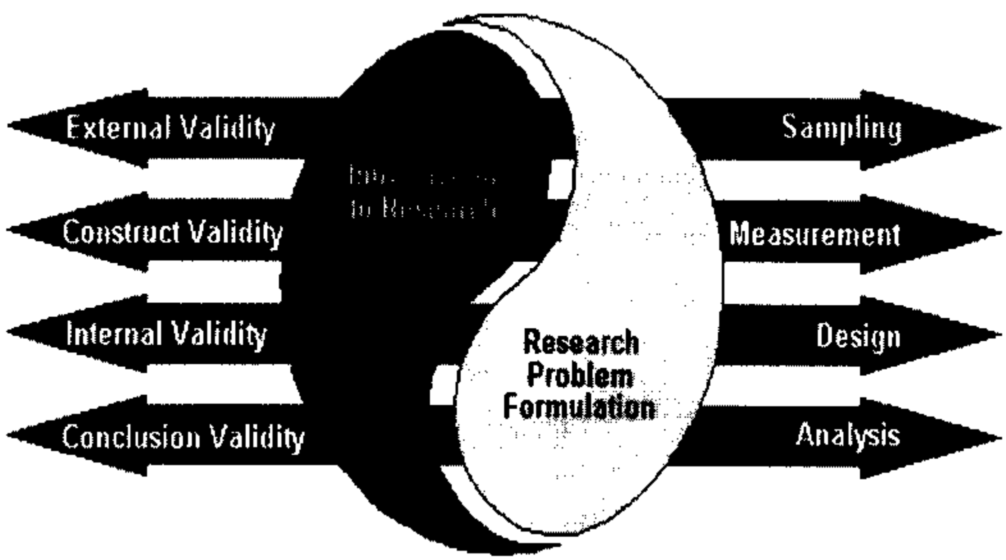
H_0: *there is no statistically significant relationship between the proposed SC characteristics and the state of systemic thinking at the individual level that would indicate predisposition for engaging in the complex problem domain.*

The results of the analysis showed that a statistically significant relationship does indeed exist between the proposed Sc characteristics and the state of system thinking that indicates a predisposition for engaging in the complex problem domain. Based on the results, the researcher has rejected the null hypothesis, thus lending support to the alternative hypothesis (H_1).

VALIDITY OF THE SYSTEMS THINKING INSTRUMENT

To answer the question "is the survey tool valid?" in such a mixed method research, the researcher conducted different types of validity tests: face validity, content validity, constructive validity, external validity and conclusion validity. The researcher adopted Yin and Yang (2003) and Trochim's (2000) paradigm of validity to describe the types of validity and their relationship to the research. It is important to mention that the validity types build on one another, and they are for all stages of research.

Figure 4.13: The Yin and Yang Research



(Adopted from Yin and Yang, as cited in Creswell, 2008)

FACE VALIDITY

The analysis of factor analysis, specifically the obtained correlation matrix, established that the variables (questions) seem to measure what they were intended to measure. For instance, reviewing the matrix (Table 4.9) shows that there is a correlation between the variables, which makes the results more reliable and accurate. In addition, the researcher sent the survey instrument to several experts to gather their comments and suggestions. The researcher also sent the survey instrument to "peer debriefing" and used external auditors who were unfamiliar with both the research and the researcher.

CONTENT VALIDITY

Content validity highlights the question: does the measurement's meaning reflect the purpose and the objective of the study? (Babbie, 2010; Creswell, 2008; O'Sullivan et al. 2007) The results established that the content of the 39 questions are loading well on the five extracted factors (Tables 4.14, 4.15). This reveals that the 39 questions have high loadings with excellent validity and appear to truly measure the level of systemic thinking.

CONSTRUCT VALIDITY

Construct validity describes the relationship of the operational description of the variables to their conceptualization (Babbie, 2010). To measure the level of systems thinking, the researcher has developed a systems thinking instrument. This instrument measures the theoretical framework (7 Sc) characteristics obtained from grounded theory coding. The results of the eigenvalues, unrotated and rotated components matrixes showed that the new systems thinking instrument does indeed measure and capture the systems thinking at the individual level with respect to complex problem domain.

EXTERNAL VALIDITY

External validity is related to the generalizability of the study, e.g. from a sample to a population which is based on establishing the domain of a study. (Trochim, 2000) External validity provides the basis for generalizability of research findings to different groups, settings and times. In other words, the findings of research should "have implications for other groups and individuals in other settings at other times." [Trochim, (2000), p. 22] According to the Kaiser-Meyer-Olkin test, and the readout of Anti-image correlation and covariance matrixes, the dataset is well suited for factor analysis. This means that (1) the results of the analysis are reliable, and (2) there is a high possibility of generalizing the results beyond the collected sample. While this instrument has shown promise based on testing of internal validity, external validity has not been established. A follow up research will be conducted to establish the external validity of the systems thinking instrument for application as a domain-free tool to determine the level of systemic thinking for an individual.

CONCLUSION VALIDITY

Based on the results, the researcher has rejected the null hypothesis.

RELIABILITY OF THE SYSTEMS THINKING INSTRUMENT

Reliability is another important concept in research. The term Confirmability could also be used to describe reliability. (Babbie, 2010; O'Sullivan et al. 2007) Reliability has to do with the "repeatability" and "consistency" of a measure. The measure is reliable if the results are the same repeatedly; a technique applied repeatedly to the same object should yield the same results each time. (Trochim, 2000; Babbie, 2010; Creswell, 2008) In this research reliability is assessed in three forms:

1. Pilot test,
2. Chronbach's Alpha reliability,
3. Parallel reliability.

PILOT TEST

The researcher ran a pilot test on the instrument for three main purposes: (1) to reduce the random errors and systematic errors in the measurement. Measurement errors have a direct impact on the reliability of the instrument. "Errors in measures play a key role in degrading reliability." [Trochim, (2000), p.88], (2) to apply some appropriate statistical procedures to adjust the measurement errors, and (3) to get some feedback and suggestions.

After conducting a pilot test before the deployment of the systems thinking instrument, the research used factor analysis and Monte Carlo Simulation to analyze the dataset obtained from two hundred and forty two participants. The results of the analysis showed that (1) the new survey instrument measures and captures the level of systems thinking for individuals, and (2) there is a possibility of generalizing the results beyond the collected sample.

Chronbach's Alpha Test (α) and Parallel Test

Besides the pilot test and experts' evaluation, the researcher performed various reliability tests for the internal consistency of the systems thinking instrument. These included Cronbach's Alpha and Parallel reliabilities. There are some rules (Table 4.18) of thumb of assessing the internal reliability that are suggested from different scholars (George and Mallery, 2003; Maxwell, 1992).

Table 4.18: Reliability Scale

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	Poor
[illegible]	[illegible]

In order to obtain internal reliability of the survey instrument, Cronbach's Alpha test and Parallel Reliability test were conducted; the results, respectively, were 0.811

(very good) and 0.811 (Tables 4.19, 4.20). As illustrated in Table 4.19, the survey instrument has a very good reliability measurement. This means that the survey instrument reliably measures the state of systems thinking at the individual level for engaging in the complex problem domain.

Table 4.19: Cronbach's Alpha (α) Test

Reliability Statistics		
[redacted]		
.811	**.811**	39

Table 4.2: Parallel Reliability

Reliability Statistics	
[redacted]	
True Variance	.020
[redacted]	
Common Inter-Item Correlation	.102
[redacted]	
Reliability of Scale (Unbiased)	.813

The following is a summary of the relationship between reliability and validity (Babbie, 2010; Creswell, 2008; O'Sullivan, et al. 2007).

- Reliability is a necessary but insufficient condition to achieve validity. Therefore, if we have a reliable measure of a concept, it does not guarantee that the measure will be valid.
- Validity implies much more than reliability and a measure can be reliable but invalid.
- If the measurement instrument is not valid, its reliability cannot be considered.
- Controlling for threats to internal validity often results in reduced external validity of those findings.

CONCLUSION

The idea of factor analysis is to reduce the chunk of data into a more manageable and organized set of factors (variables). After conducting component factor analysis (CFA), the output of the analysis has shown that some variables were invalid and would likely be dropped from the analysis and therefore the survey. To improve the systems thinking instrument and make it more efficient, five variables were omitted from the survey instrument. Figure 4.14 shows the five omitted variable.

Figure 4.14: Omitted Variables

Omitted Variables	Communalities Extraction
System understanding is more preferable at which level: a. local level b. global level	0.159 <0.4
For this scenario, there are multiple perspectives that are: a. correct b. incorrect	0.19 < 0.4
Uncertainty in a situation should be a. avoided b. expected	0.176 <0.4
The level where change in a system is best implemented is: a. local b. global	0.191 <0.4
With complex problems, there is usually: a. an identifiable cause b. not an identifiable cause	0.181 <0.4

These variables were omitted based on (1) communalities values, (2) unrotated component matrix and (3) rotated component matrix. The communalities values of these variables were very low <0.3, which indicates that these variables are not reliable and will have a negative effect on the extracted factors. In addition these values have low loadings (rotated matrix) or no loadings at all on the extracted factors. This means that the content of these variables does not measure the level of systems thinking.

To test the reliability of the instrument, the researcher conducted different test types, including Cronbach's Alpha Test (α) and Parallel Test (Tables 4.20, 4.21) and the results were very good (81%). This reveals that this instrument is reliable and measures what it is supposed to measure. Reliabilities less than 60% are generally considered to be poor, those in the 70% range, to be acceptable, and those in the 80% range to be good (Sekaran, 2003). To check the validity of the new systems thinking instrument, multiple validity checks, including face validity, internal validity, conclusion validity and content validity were engaged. The reliability of the instrument was established and validity supported by statistical tests.

In conclusion,

1. Based on the sample size, the researcher obtained variables with eigenvalues much greater than > 0.3;
2. The new systems thinking instrument consists of 39 questions instead of 44;
3. These questions truly measure the level of systems thinking;
4. The results of the analysis are promising and very interesting.

SUMMARY

This chapter has shown the results and interpretation of the research. It has two main elements: the steps for component factor analysis and a review of survey validation and reliability. This chapter fulfilled the purpose of the research and answered the two main research questions. In this chapter, the researcher rejected the null hypothesis, thus lending support for the alternative hypothesis. Importantly, the chapter established the validity and reliability of the new systems thinking instrument. The results of the analysis are very promising. Monte Carlo simulation provided additional validity for the instrument. Six variables have been omitted; thus, the new survey instrument consists of 39 questions rather 44 questions. Of the 242 participants, 241 were included in the analysis. The next chapter will discuss the implications and areas of future research.

CHAPTER V

CONCLUSION

This chapter provides a summary of the research, identifies the threefold contributions of the research across theoretical, methodological and practical dimensions, and makes recommendations for future research based on the findings and results.

Chapter I showed the purpose and significance of the research and the structure of the inquiry including the research questions and hypothesis. It also conceptualized several specific terms the researcher used throughout the research. Chapter I addressed the limitations of the study as well as the strategies used to address these limitations. It also highlighted the contribution of the research across theoretical, methodological and practical dimensions and positioned the research as an original contribution to the complex systems problem domain.

Chapter II formed the boundary of the literature and identified the literature review schema. It also provided an extensive review of system theory, complex systems/SoS, and systems thinking literature. In this chapter, the researcher constructed a histogram analysis for system of systems; the purpose of the histogram was to (1) alleviate the confusion related to the different terminologies used to describe SoS, (2) trace the development of complex problems domains from 1926-2011 against the backdrop of SoS, and (3) determine the peak of the development. In this chapter the researcher also showed the major synthesis in the literature, provided scholarly critique and identified the main gaps that feed the research efforts.

Chapter III proposed three phases to conduct the research in order to achieve a rigorous research design. Phase I identified the systems thinking characteristics (framework) that are essential to engage complex problem domains. Phase II applied the systems thinking characteristics (7 core codes) at individuals and provided a comprehensive definition for each systems thinking characteristic. In phase III the researcher developed a systems thinking instrument to capture the individual's predisposition for systems thinking through interaction with a scenario. In this phase the researcher also tested the capability of the systems thinking instrument to capture and measure the systems thinking characteristics emerged from phases I and II. The purpose of this chapter was to develop a robust research approach. A mixed methods (quantitative and qualitative) research design with three phases was constructed; the three phases of the research design were the blueprint the researcher used to develop the new systems thinking instrument. This research used an inductive research design, grounded theory coding, and specific software (Nvivo) to analyze a thousand different literature sources to derive the systems thinking characteristics individuals need to engage complex problem domains. Three procedures were adopted in grounded theory coding, including open coding, axial coding and selective coding. The systems thinking instrument was constructed to measure the level of systems thinking of individuals who engage in complex problems domains. This instrument consists of 39 binary questions with a scenario that describes complex system problems.

Chapter IV presented the results of the research. Descriptive statistics showed the patterns in the dataset, and factor analysis was used to validate the systems thinking instrument. *Normality Sampling Adequacy* tests were conducted to check the suitability of using factor analysis to the dataset and a *Communalities table* was obtained to observe how many variables might load on factors. A *Correlation Matrix and the Bartlett's Test of Sphericity* were obtained to check the intercorrelations between the variables. A "*Total Variance Explained Table*" explored the underlying extracted factors with eigenvalues.

Three main criteria were used to factor extractions, including: (1) factors that have eigenvalues > 1 (Kaiser's criterion of retaining), (2) the scree plot (elbow curve), and (3) the Monte Carlo simulation (parallel analysis). *Rotated and Unrotated Component Matrixes* were used to interpret the extracted factors and make a final decision. In chapter IV, the researcher accepted the alternative hypothesis (*there is a statistically significant relationship between the proposed SC characteristics and the state of systemic thinking at the individual level that would indicate predisposition for engaging in the complex problem domain.*) and rejected the null hypothesis.

To check the validity of the instrument, multiple validity checks, including face validity, internal validity, conclusion validity and content validity were engaged. To check the reliability of the instrument, the researcher conducted different tests namely Pilot test, Chronbach's Alpha and Parallel tests. The reliability of the instrument was established and validity supported by statistical tests.

IMPLICATIONS OF THE RESEARCH

This section shows in depth the implications of the research across theoretical, methodological and practical dimensions.

THEORETICAL DIMENSION

From a theoretical dimension, this research contributed by developing a framework that consists of seven main characteristics that label large socio-technical problems. As mentioned throughout the discussion in chapter II there is no significant agreement on the characteristics that constitute complex systems problems. Therefore, the purpose of the framework is to lessen the confusion with respect to the main characteristics pertaining to large complex systems. It is imperative to mention that these characteristics were derived after analyzing a thousand sources. These characteristics are the most coded in the literature describing large complex systems.

Another main contribution the research added to the body of knowledge is that it identified the set of systems thinking characteristics individuals need to engage in complex problem domains. There is no single study in the current literature that mentions or describes such characteristics. Several studies focus on providing characteristics for complex problems without paying attention to the necessity of having systems thinking capabilities for individuals who engage with these problems. The set of systems thinking characteristics serve as an infrastructure for individuals who deal with complex systems environments.

Correlation and mapping the systems thinking characteristics to the Myers-Briggs Type Indicator instrument is another contribution the research added to the literature. Each systems thinking characteristic was assessed using David Keirsey and Marilyn Bates questions (Keirsey, 1998). The purpose of mapping was to provide individuals with their personality type alongside their systems thinking profile (Appendix E and F)

METHODOLOGICAL DIMENSION

From a methodological dimension, this research contributed by developing a new systems thinking instrument to capture the level of systems thinking for individuals who engage in multidisciplinary complex problems. This survey instrument is specifically designed to deal with complex problems. As mentioned throughout the dissertation, there are no tools or techniques purposefully designed to assess the systems thinking capacity of individuals related to dealing with multidisciplinary complex problems. The current tools and techniques are either adopted or extrapolated from different fields such as Systems Engineering. The researcher does not mean to be critical of the current techniques and tools that those in other fields have developed. In fact, these tools and techniques have succeeded in problems that have technical issues, but they have not achieved the same level of success when applied to problems that have organizational/managerial, political/policy and human/social dimensions. The new systems thinking instrument is purposefully designed to focus more on these dimensions with problems of an ambiguous, uncertain, and dynamic nature, and more specifically, the capacity of individuals for engaging those problem domains.

Another contribution the research added from a methodological dimension is that the survey instrument provided a set of different profiles that determine the level of systems thinking for individuals. The seven pairs of preferences provide a better understanding of the individual's capacity to deal with multidisciplinary complex problems. There is a broad collection of methods, techniques, technologies, and tools that can be used in dealing with those problems. However, these methods have not been purposefully coupled with the individual capacity to engage the tools at a commensurate level of systems thinking.

The research has focused on developing a non-domain specific systems thinking approach to identify people with a worldview consistent with success in the complex systems domain. This research has applicability across several sectors ranging from transportation to education to healthcare to industry and others. Systems thinking skills are needed in any field or discipline where individuals should have the systems thinking capabilities to deal with multidisciplinary complex problems. As discussed in chapter IV, the research results showed a high possibility of generalizing the results beyond the collected sample demonstrating that the instrument is not restricted to one particular field. The thirty-nine questions and the scenario provided in the survey instrument are designed to be general in nature for any complex problem without restriction to field or situation.

PRACTICAL DIMENSION

The researcher explored the development of an instrument to determine at which level of systems thinking an individual can be classified. This research has applicability across many sectors (e.g. industry, healthcare, energy, transportation, security, education) where individuals must deal with a domain marked by increasing complexity, high levels of interconnectivity, uncertainty and ambiguity. Dealing with these problems requires individuals to gain more knowledge by looking at a holistic spectrum of dimensions of the problem that cross social, managerial, organizational, and political dimensions. In response, the focus of this research develops a method and corresponding instrument to understand how adept individuals are at engaging in the kind of systemic thinking necessary to effectively navigate the multidisciplinary complex system problems from a more holistic perspective.

The outcome of this research provides an instrument to develop a profile that assesses the level of systems thinking for an individual. Ultimately, this instrument provides a basis to help engineers, business leaders, managers, and other professionals to determine individual capacity for dealing with complex problem domains. Further, this instrument could serve as a foundation to inform the development of individual and organizational development programs for increased effectiveness in systems thinking. Additionally, a range of new tools and methods to increase effectiveness of systems thinking for complex system problems can be suggested from the research into this instrument. The following shows some of the applications of this research from a practical dimension:

- This research provides an instrument to develop a profile that assesses the level of systems thinking for an individual. As mentioned in chapter III, this research developed an instrument that contains several systems thinking profiles. Each profile gives a clear description of how an individual approaches complex problems. It is important to mention that these profiles have applicability across several fields since systems skills capabilities are needed in any field.
- This research offers a starting point to better understand individual capacity to engage complex multidimensional problems. To better understand the nature of complex problems, it is necessary to know the profile type of systems thinkers who are engaged in solving these problems. The systems thinking instrument helps to gain this knowledge by providing systems thinking profiles.

- Match individual potential with job requirements by assessing the level of systems thinking for an individual. The systems thinking instrument does not measure personality preferences, rather it measures the level of systems thinking. This means that leaders, managers, and others will be able to assign the right job requirement for individuals by looking at their Sc profiles. For example, if an individual is a "S" type systems thinker, then he/she leans more toward working in problems that are simple with a clear cause-effect relationship. On the other hand, if the individual is a "C" type systems thinker, then he/she enjoys working in large complex problems where uncertainty occurs .This is another practical application of the research. In addition, for particular jobs, the results of the profile might indicate particular development objectives to better position existing personnel for success in their jobs that might require higher capacity for systems thinking.
- Set more realistic organizational goals by including a broader range of levels of systems thinking. To have effective strategic planning in any system, it is important to recognize the type of systems thinkers in the system (organization). For example, if the majority of the employees in an organization are "Autonomy" type systems thinkers, who focus more on the local performance, and the goal of the organization is integration, this would create difficulty in achieving this goal. Thus the seven preferences pairs can be useful in balancing the organization's goals with its resources.
- Provide better understanding of the different types of systems thinkers required for specific job classifications. Having too many "H" holism type systems thinkers and no "R" reductionism type systems thinkers in an organization might cause failure in

solving problems that need to be discretely parsed into manageable elements. Individuals that emphasize "Emergence" preference tend to focus on the whole, keep options open, and avoid detailed plans. While individuals that emphasize "Stability" preference tend to focus on the details and prepare detailed plans in advance.

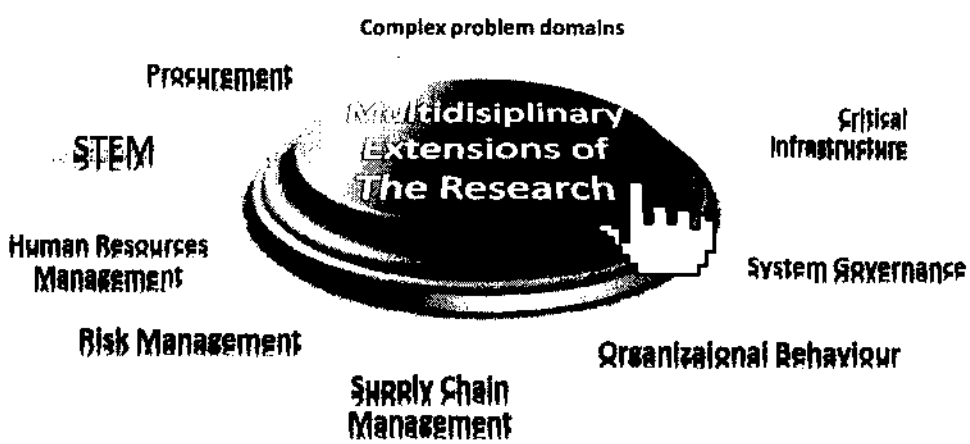
- This research encourages individuals to examine their own preferred ways in solving complex problems. The different systems thinking profiles help individuals to assess and improve their ways in solving complex problems by reviewing the benefits of each preference. Similarly, by knowledge of the systems thinking profile of those organizational members that an individual must interface, might inform better collaborative approaches – fit to the particular systems thinking capacity of team members.
- The systems thinking instrument is considered an intervention tool at multiple levels: individuals, organizations, teams, and others. It helps responsible professionals to more effectively form teams based on their systems thinking profiles and compatibility with the complexities faced in the problem domain in which they are anticipated to be deployed.
- The systems thinking instrument is the only tool that explains human systems thinking preference type. There is currently no such instrument in the field.
- The systems thinking profiles can help individuals, organizations and others in understanding the influence of their level of systems thinking with respect to taking actions and making decisions within complex problem domains.
- This research provides an indicator of an individual developmental (training and education) needed to improve the individual capacity for systems thinking.

FUTURE RESEARCH AND RECOMMENDATIONS

The results from this follow-on research would provide individuals with research based guidance to classify the level of systems thinking for individuals who must become more effective in working within multidisciplinary teams on complex problems.

Rigorous scholarly research should provide recommendations and identify prospects for future research. This last section is allocated for this purpose. Since the research has applicability across several sectors (i.e. industry, education and others), there are many interesting areas for further investigation and research to be addressed. Figure 5.1 below depicts the multidisciplinary extensions of the research.

Figure 5.1: Future Research Areas



The following are some of these areas based on the findings and results:

PERSONALITY THEORY (MBTI)

For future research, the researcher mapped and linked the systems thinking characteristics to the Myers-Briggs Type Indicator instrument as illustrated in Appendices E and F. The purpose of this mapping is to link the systems thinking profile with the suitable personality profile. Appendix E provides a brief history of MBTI and shows the structure of MBTI. Appendix F presents the mapping process and provides input for future research. The anticipated future research is to explore if there is a correlation between the Sc profile and personality type profile. The type of correlation will determine if the personality types of individuals affect their approach and capacity for engaging complex problems. Research in this area is needed to answer the following main question:

Does personality type affect the approach individuals take to solve multidisciplinary complex problems?

ORGANIZATIONAL BEHAVIOR

During the data collection process, the researcher collected demographic information of the participants for future research. Research in this area is needed to study the exploration of the effects of demographic factors (age, sex, race) on the state of systems thinking at the individual level to deal with complex problem domains. Further research should include the effect of educational level, work experience, and leadership experience on the capacity for systems thinking. The question becomes:

What is the relationship between different demographic classifications and the approach individuals take to engage in complex problem domains?

COMPARISONS STUDIES

From discussion in the literature, the researcher found three main perspectives with respect to SoS: academia, military and industry/business. The sample of the study included participants from the three perspectives. A comparison is needed to explore the effects of work environment on the state of systems thinking at the individual level to deal with complex problems from academia, military and industrial perspectives. Further research is needed to study the effect of the individual current occupation as an engineer or non-engineer on the level of systems thinking. Another potential direction for research that could be interesting is to study the effect of family size on the level of systems thinking for individuals. The main questions that need answer are:

How work environments affect the level of systems thinking of an individual to deal with multidisciplinary complex problems?

Does the number of family members affect an individual's approach in solving complex problem domains?

SYSTEMS GOVERNANCE

The concept of system governance has grown in the last decade. To achieve a good system governance design, it is necessary to have a solid foundation of individuals who have the systems skills needed to deal with system governance. The idea here is that the instrument can build this foundation and make it explicit. In this area the research must move forward to capture the capabilities individuals need to understand and engage complex system governance. An interesting question to establish is:

What are the systems thinking capabilities individuals should possess to effectively engage complex system governance?

The systems thinking instrument will be able to support derivation of the set of capabilities individuals need.

SUPPLY CHAIN MANAGEMENT

Supply Chain Management is one of the increasingly important topics in the last decade. The complex nature of supply chains stems from the more holistic consideration of human/social, organizational, managerial, and political dimensions. Dealing with this complexity requires supply chain managers to enhance capabilities for holistically looking at the entire spectrum of supply chains. In response, the focus of my research develops a method and corresponding instrument that will help to understand how adept supply chain managers are at engaging in the kind of systems thinking necessary to effectively navigate the supply chain problems across the spectrum of holistic dimensions that are characteristic of the complexities faced by modern supply chain management. I believe the research has a strong organizational and leadership component related to supply chain management. A specific research question should be focused on:

What are the characteristics supply chain managers need to deal with the complex nature of supply chain?

HUMAN RESOURCE MANAGEMENT

In the domain of human resources management, the research can provide utility by fitting individuals in the right positions to be successful in their jobs. For example, if the job profile requires individuals with a high level systems thinking skills, then it is appropriate to hire "holism" type systems thinkers, or engage development programs to grow individuals with this capacity. On the other hand, if the job profile requires individuals with a focus on a reductionism based approaches, then it is appropriate to hire a reductionist oriented thinker. The instrument can provide further implications for the human resources management field and move it forward by providing utility in the following areas:

- Measure and match the individual systems thinking skills with the job profile and requirements.
- Present a set of systems thinking profiles that distinguish the different systemic thinking skills from one individual to another. The appropriateness of these profiles is based primarily on the nature of the complex problem. The research question becomes:

  How to assign the right job profile to the right individual systems thinking profile?

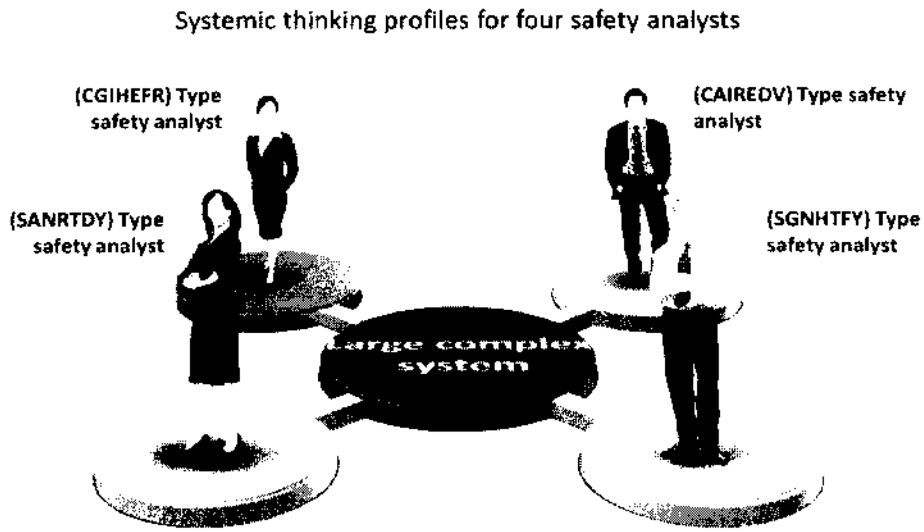
RISK MANAGEMENT

Safety professionals have realized that traditional system engineering (TSE) has many limitations to applying efficient safety behaviors in the integrated complex system domain. This domain is marked by increasing complexity, excessive information, ambiguity, and high levels of uncertainty. Dealing with these problems requires knowledge not only of technological issues, but also of the inherent human/social, organizational/managerial, and political/policy dimensions that solutions to these issues must consider. Increasing complexities and the huge interrelated components of systems bring to question the ability of safety professionals to effectively deal with these problems. One of the major challenges safety professionals inevitably face when working within complex systems is how to enhance safety behaviors in these complex systems.

The design of system safety in such complex systems requires safety analysts to have a high level of systems thinking skills to ensure safe and resilient system safety design. This research can contribute to risk management in the following areas:

- Provide taxonomy of systems skills that are needed in risk management.
- Capture the state of systems thinking at the individual level that would indicate predisposition in conducting safety analysis in a large complex problem.
- Match systems analysts skills with the job requirements. Figure 5.2 below shows an example of how to match the appropriate safety analyst to design for safety in large complex problem. The individual who stands on the green patch with the (CGIHEFR) letters is the most appropriate one to design for safety in this large complex system. This safety analyst has the highest level of systems thinking among the group and her systems skills are vital to the system under study.

Figure 5.2: System Skills Profiles



An interesting research question would be:

What are the set of systems skills safety analysts need to design a rigorous safety system for complex problem domains?

GOVERNMENT PROCUREMENT

When the government procures a constituent system, it will select the contractor who will provide the prime value. However, when the government procures multiple integrated systems or system of systems it is difficult to obtain the one best value because several good options might be available. This difficulty is actually driven from the complex nature of a procurement system. This is especially the case since the domain of procurement is characterized as having any combination of the following characteristics:

complexity, divergence, excessive information, high level of ambiguity and uncertainty, emergence and shifting requirements. These characteristics typify the real-world experiences of procurement practitioners. All of these characteristics become design issues for a procurement system.

To deal with the complex nature of procurement systems, the design of this system should be flexible and adaptable. The question becomes, what are the capabilities the procurement practitioners need to design a good procurement system? In other words, what type of systems thinker is needed to ensure a good procurement design to withstand the complex nature of procurement?

The contribution of this instrument is to provide further development to the domain of procurement and move it forward. To do this, the systems thinking instrument can provide utility in the following areas

- Provide better understanding on how to design a procurement system that recognizes the complex world of procurement officers.
- Provide compatibility between the procurement system and the architect (procurement designer).
- Provide a set of profiles that determine the level of systemic thinking for individuals who execute procurement activities.

An interesting research question would be:

What are the set of systems skills individuals need for better design and development of system governance in complex systems?

STEM EDUCATION

Another future area of research can be within the STEM field. Research is needed to study what should be included in STEM education from complex system, system theory and system of systems perspectives. The principle question that needs to be answered are:

What qualifications (systems skills) should an engineer attain to be successful in the engineering domain?

What should be included or excluded from the curriculum to ensure systems thinking capabilities?

SUMMARY

In conclusion, this chapter provided a summary of the dissertation chapters and presented the implications of the research from three perspectives; theoretical, methodological, and practical. Future research paths were identified with an emphasis on eight main areas: Personality Preference, Organizational Behavior, Comparison Studies, System Governance, Logistics and Supply Chain Management, Risk Management, Government Procurement and STEM Education. This chapter also showed the multidisciplinary extensions the research can provide across many fields as exhibited in Figure 5.1.

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APPENDIX A

OPEN CODING NODES

Autonomy
Autonomy\Geographical distribution
Autonomy\Manage interface design (Open interface)
Autonomy\Managerial independence
Autonomy\Operational independence
Complexity
Complexity\Contextual influences
Complexity\Contextual influences and systemic barrier\Appropriateness of tools to the context and problem
Complexity\Costly systems
Complexity\Incomplete understanding of SoS
Complexity\Lack of specific methodology
Complexity\Lack of specific methodology\Departure from traditional systems engineering
Complexity\Lack of specific methodology\Embryonic state in SoS
Complexity\Lack of specific methodology\Insufficient tools and methods
Complexity\Lack of specific methodology\New discipline focuses on large complex systems
Complexity\Lack of specific methodology\New techniques for complex problems
Complexity\Lack of specific methodology\No accepted definition for SoS
Complexity\Large scale systems
Complexity\Systemic barrier
Emergence
Emergence\Dynamic in nature
Emergence\Dynamic in nature\Ambiguity
Emergence\Dynamic in nature\Ambiguity\Ambiguous Boundaries
Emergence\Dynamic in nature\Turbulent environment
Emergence\Dynamic in nature\Turbulent environment\Open Systems
Emergence\Dynamic in nature\Uncertainty
Evolutionary development
Evolutionary development \Continuous life cycle
Evolutionary development \Direct control is impossible (control requirements)
Evolutionary development \Multiple perspectives (richness)
Evolutionary development \Multiple perspectives (richness)\pluralistic
Evolutionary development \Satisficing solutions
Evolutionary development \Satisficing solutions\Ill structured problems
Evolutionary development \Satisficing solutions\Interdisciplinary problems

APPENDIX A

"CONTINUED"

Evolutionary development \Satisficing solutions\Multidimensional problems
Evolutionary development \Satisficing solutions\Social-technical problems
Evolutionary development \Self organization
Evolutionary development \SoS is not monolithic
Flexibility
Flexibility\Adaptability
Flexibility\Creativity
Flexibility\Design for resilience
Flexibility\Distributing power and authority
Flexibility\Distributing power and authority\Centralization
Flexibility\Distributing power and authority\Governance system (control and manage the components)
Flexibility\Distributing power and authority\Toward decentralization
Flexibility\Responsiveness
Holistic perspective
Holistic perspective\Focus on entire problem
Holistic perspective\Focus on methodology
Holistic perspective\Focus on the whole
Holistic perspective\Multidisciplinary approach
Holistic perspective\Systemic way
Holistic perspective\Systems theory to understand SoS
Holistic perspective\Systems theory to understand SoS\SE and SoS
Holistic perspective\Systems theory to understand SoS\SE and SoS\SoSE and SoS
Holistic perspective\Systems theory to understand SoS\Systems thinking
Holistic perspective\Transdisciplinarity is needed
Holistic perspective\Visionaries and coordinators
Interconnectivity
Interconnectivity\Collaboration is needed in SoS
Interconnectivity\Communications
Interconnectivity\Communications\Common language
Interconnectivity\Connectivity
Interconnectivity\Federalism
Interconnectivity\Integration of multiple individual complex systems
Interconnectivity\Integration of multiple individual complex systems\Authority of integration
Interconnectivity\Integration of multiple individual complex systems\Autonomous individual complex systems

APPENDIX A

"CONTINUED"

Interconnectivity\Integration of multiple individual complex systems\Belonging
Interconnectivity\Integration of multiple individual complex systems\Heterogeneous Systems
Interconnectivity\Integration of multiple individual complex systems\Joint systesms
Interconnectivity\Integration of multiple individual complex systems\Meta-systems
Interconnectivity\Integration of multiple individual complex systems\Net of systems
Interconnectivity\Integration of multiple individual complex systems\Produce a new behavior (higher capabilities and performance) not achievable by any individual system
Interconnectivity\Network of systems (The structure)
Interconnectivity\Integration of multiple individual complex systems\Wicked-connected systems

APPENDIX B

DEMOGRAPHIC QUESTIONS

1. **Gender**
    a) Male
    b) Female
2. **Education level**
    a) Some high school, no diploma
    b) High school graduate, diploma or the equivalent
    c) Some college credit, no degree
    d) Trade/technical/vocational training Associate degree
    e) Bachelor's degree
    f) Master's degree
    g) Professional degree
    h) Doctoral degree
3. **Field of highest degree**
    a) Engineering
    b) Management
    c) Others
4. **What best describe your current occupation**
    a) Engineering
    b) Non engineering
    c) Student
    d) Others
5. **Work experience**
    a) 5 years and below
    b) (6-10) years
    c) (11-15) years
    d) (16-20) years
    e) 21 years and above
6. **Ethnicity/Race**
    a) White
    b) Hispanic or Latino
    c) African American

d) Asian/Pacific Islander
e) Others

7. Family size

a) Small (3 or less)
b) Large (3 and above)

8. Employer type

a) Academic institution
b) Industry
c) Military
d) State or federal agency
e) Others

9. Organization you work for is

a) Public sector
b) Private sector/profit
c) Private sector/Not-for-profit
d) Others

10. Managerial/supervisor experience

a) 5 years and below
b) (6-10) years
c) (11-15) years
d) (16-20) years
e) 21 years and above

APPENDIX C

SYSTEMS THINKING (Sc) QUESTIONNAIRE

Thank you for agreeing to participate in this web-based-survey.

In this survey you will respond to a set of questions, which will take approximately 8 minutes to complete, you will answer questions related to a web-based scenario. ***This survey instrument captures the state of systemic thinking at the individual level that would indicate predisposition for engaging in the complex problem domains characteristic of the 21st century. This research instrument will generate an individual systems thinking profile.***

Please enter your name and e-mail address to receive your specific results (systemic thinking profile) with a guide for interpretation. Your results will be in confidence. Your name and email address will ONLY be used to send you the score of your results.

E-mail address

Please indicate your selections for each question.

Scenario
"The following scenario provides a description and background of a complex company. The questions following the scenario are general in nature and only intended to assess your thinking about any complex situation, such as this scenario." **Please select the answer that is the best choice for you. There are no right or wrong answers.**

You are a member of a large scale export management company that ships a variety of goods and services worldwide. The company was established over 30 years ago with one geographic location and one primary product. Over the years, the company has acquired several smaller companies to expand the product offerings, customer base, and global presence. The different units of the company are part of a larger system but remain geographically separated and operate somewhat autonomously, with separate operations, management, and performance goals. Product performance and customer expectations have generally been exceeded at the individual unit level. **For each statement, please select the response that you personally agree with the most.**

1. To address system performance focus should be on
   a. individual members of the system
   b. interactions between members of the system

2. Do you prefer to work with
   a. few systems or people
   b. many systems or people

3. Are you most comfortable developing a
   a. detailed plan
   b. a general plan

4. Do you prefer to
   a. work individually on a specific aspect of the problem
   b. organize a team to explore the problem

5. With respect to system interactions, at which level would you prefer to focus
   a. locally
   b. globally

6. Do you feel more comfortable working
   a. individually
   b. in a group

7. Which is more important to preserve
   a. local autonomy
   b. global integration

8. Decisions should be made
   a. independent of the system
   b. dependent on the system

9. Parts in a system should be more
   a. self-reliant
   b. dependent

10. Giving up local decision authority should be
    a. resisted
    b. embraced

11. Performance is determined more by actions at the
    a. local level
    b. global level

12. Do you prefer to think about the time to implement change in a system as
    a. short
    b. long

13. Change in a system is most likely to occur as
    a. evolutionary
    b. revolutionary

14. In turbulent environments, planning for system change is
    a. useful
    b. wasteful

15. Forces for system change are driven more
    a. internally
    b. externally

16. To evolve a system, would you prefer to find
    a. One best approach
    b. Multiple possible approaches

17. To ensure system performance, it is better to
    a. underspecify requirements
    b. overspecify requirements

18. Would you most prefer to work in a group that
    a) prepares detailed plans beforehand
    b) reacts to situations as they occur

19. You prefer to focus more on the
    a) specific details
    b) whole

20. In dealing with unexpected changes, you are generally
    a) uncomfortable
    b) comfortable

21. Control of the work environment is
    a) possible
    b) not possible

22. I prefer to work on problems for which the solution is
    a) objective
    b) subjective

23. I most enjoy working on problems that primarily involve
    a. technical issues
    b. non-technical issues

24. Are you more inclined to work on something that follows
    a) regular patterns
    b) irregular patterns

25. Once desired performance is achieved, a system should be
    a) left alone
    b) adjusted

26. In dealing with a system, would you prefer it to be
    a) small
    b) large

27. I prefer to work on problems for which the approach is
    a) standardized
    b) unique

28. In solving a problem, I generally try to get opinions from
    a) a few people
    b) many people

29. A solution to a problem should always be
    a) the best solution
    b) a working solution

30. A system can be understood by analyzing the parts
    a) agree
    b) disagree

31. In thinking about this company, I would prefer to focus on
    a) particulars
    b) the whole

32. System performance is primarily determined by individual components
    a) agree
    b) disagree

33. A problem should first be addressed at what level
    a) specific
    b) general

34. Once successful, a technical solution will result in similar success in other applications
    a) agree
    b) disagree

35. I am most comfortable working where circumstances require
    a) minimal adjustment
    b) constant adjustment

36. Once a system is deployed, modifications and adjustments indicate that the design was
    a) inadequate
    b) flexible

37. In planning for a system solution, plans should be
    a) fixed
    b) expected to change

38. With respect to execution of a plan
    a) I prefer to follow the plan as closely as possible
    b) I am comfortable with deviating from the plan

39. I would describe my preferred work environment as one for which outcomes
    a) are predetermined
    b) emerge

APPENDIX D

ANTI-IMAGE CORRELATION MATRIX VALUES

Questions	1	2	3	4	5	6	7	8	9	10
1	.710	-.050	-.067	-.012	-.067	.017	.024	-.055	-.098	.007
2	-.050	.661	-.036	-.008	.037	-.138	-.034	-.009	-.011	.026
3	-.067	-.036	.716	-.051	.052	.062	-.021	.061	.004	-.011
4	-.012	-.008	-.051	.509	-.031	-.233	-.078	-.097	.060	.015
5	-.067	.037	.052	-.031	.626	-.043	-.031	-.110	.012	.031
6	.017	-.138	.062	-.233	-.043	.538	.070	.028	-.051	-.078
7	.024	-.034	-.021	-.078	-.031	.070	.760	-.002	-.073	-.016
8	-.055	-.009	.061	-.097	-.110	.028	-.002	.673	-.024	-.079
9	-.098	-.011	.004	.060	.012	-.051	-.073	-.024	.769	-.150
10	.007	.026	-.011	.015	.031	-.078	-.016	-.079	-.150	.758
11	-.047	-.004	.028	.014	.034	.063	-.024	-.090	-.103	-.008
12	.052	-.108	.014	-.077	-.034	.121	.045	-.058	-.011	-.146
13	-.021	.054	-.040	.043	-.031	-.063	-.055	-.111	-.009	-.034
14	.033	-.007	-.076	.030	-.015	-.018	-.016	.008	.005	-.039
15	.046	-.112	.012	-.005	.007	.070	.131	-.026	.015	-.114
16	.047	.059	-.012	.043	-.029	-.052	.045	.017	-.021	.048
17	.041	.070	-.094	.063	-.018	-.048	.001	.018	.046	-.020
18	.023	-.008	-.020	.015	-.004	.070	-.019	.045	-.071	.024
19	-.001	-.094	.088	-.025	-.054	.064	-.056	.065	-.077	-.005
20	.019	.035	-.053	-.026	.014	-.061	-.048	.009	.049	-.056
21	.058	-	-	.032	-	.018	.011	-.060	.066	-.064

		.077	.029		.022					
22	.079	-.129	-.049	-.080	.001	.087	.025	.024	-.029	-.034
23	.029	.052	-.131	-.061	-.050	-.017	.029	.067	-.023	-.002
24	-.034	-.057	-.082	-.074	-.048	-.054	-.002	.063	-.003	-.054
25	.024	.021	.013	.058	.102	-.007	-.113	.009	.083	.053
26	-.006	-.038	-.046	.003	-.010	-.034	-.078	.015	.076	.011
27	-.042	.033	-.101	-.035	-.045	-.005	-.036	-.023	.025	-.045
28	-.010	-.011	-.032	-.019	-.007	-.024	-.021	-.014	.027	-.030
29	-.035	-.039	.024	.096	-.003	-.014	-.008	-.097	.092	-.010
30	.053	.022	.018	.050	-.041	-.092	-.046	-.049	.036	-.027
31	.015	-.126	-.008	.059	-.129	-.057	-.005	.023	-.029	.050
32	.032	-.061	-.006	-.045	-.028	.029	.025	-.024	-.052	.003
33	-.040	-.026	.066	-.079	-.023	-.036	.039	.025	.000	.029
34	-.069	.031	-.033	-.068	.017	.012	-.086	-.015	-.038	-.052
35	.100	.004	-.051	.004	.000	2.631E-05	.010	-.019	-.072	.011
36	-.079	-.023	-.007	-.084	-.092	.008	.056	-.040	.002	.012
37	-.142	-.006	.021	.034	.015	-.034	-.053	-.028	.040	-.076
38	.057	-.082	.009	.000	-.050	.025	-.023	.002	.096	-.098
39	-.056	.016	.004	.024	-.027	-.020	-.072	.124	-.025	.028
40	-.004	.021	-.062	-.002	.054	-.049	-.019	-.025	-.005	.052
41	-.090	.037	-.011	.015	.057	.007	.081	-.058	-.023	.027
42	-.067	.029	.050	.024	.079	-.065	-4.900E+00	.029	.027	-.026
43	.034	.058	-.035	-.072	.022	.039	-.072	.118	-.009	-.035
44	-.030	.034	.012	.025	-.031	-.008	.025	-.020	-.013	.039

APPENDIX D

"CONTINUED"

Questions	11	12	13	14	15	16	17	18	19	20
1	-.047	.052	-.021	.033	.046	.047	.041	.023	-.001	.019
2	-.004	-.108	.054	-.007	-.112	.059	.070	-.008	-.094	.035
3	.028	.014	-.040	-.076	.012	-.012	-.094	-.020	.088	-.053
4	.014	-.077	.043	.030	-.005	.043	.063	.015	-.025	-.026
5	.034	-.034	-.031	-.015	.007	-.029	-.018	-.004	-.054	.014
6	.063	.121	-.063	-.018	.070	-.052	-.048	.070	.064	-.061
7	-.024	.045	-.055	-.016	.131	.045	.001	-.019	-.056	-.048
8	-.090	-.058	-.111	.008	-.026	.017	.018	.045	.065	.009
9	-.103	-.011	-.009	.005	.015	-.021	.046	-.071	-.077	.049
10	-.008	-.146	-.034	-.039	-.114	.048	-.020	.024	-.005	-.056
11	.735	-.050	-.042	-.101	.082	-.035	-.064	.147	.138	-.019
12	-.050	.745	-.045	.035	.022	-.090	.035	.017	.047	-.031
13	-.042	-.045	.740	-.048	-.099	-.131	.048	-.097	-.057	.038
14	-.101	.035	-.048	.745	.082	.000	.099	-.029	-.034	-.004
15	.082	.022	-.099	.082	.743	-.111	-.063	-.001	.076	-.030
16	-.035	-.090	-.131	.000	-.111	.746	.030	.039	-.031	.084
17	-.064	.035	.048	.099	-.063	.030	.692	-.050	-.074	.135
18	.147	.017	-.097	-.029	-.001	.039	-.050	.821	-.047	-.091
19	.138	.047	-.057	-.034	.076	-.031	-.074	-.047	.663	-.145
20	-.019	-.031	.038	-.004	-.030	.084	.135	-.091	-.145	.814
21	-.057	-.008	.134	.080	.012	-	.030	-	.043	-

						.046		.052		.034
22	-.005	.040	-.022	.052	-.020	-.058	-.182	.021	.061	-.012
23	.022	.002	.013	-.099	-.069	.062	-.034	.072	-.057	.043
24	-.021	-.007	.057	.000	.074	-.085	.003	-.013	.044	.043
25	.032	-.019	-.016	-.021	.031	-.099	-.003	.073	.001	-.029
26	-.012	-.009	-.007	.017	-.020	.035	-.030	-.034	-.037	-.063
27	-.070	.054	.031	.023	.012	-.089	.090	-.084	-.029	.028
28	.044	-.014	.021	-.027	-.007	-.003	-.087	-.063	.020	.085
29	-.036	.052	-.013	.134	-.042	-.022	.047	-.020	.028	-.054
30	-.071	-.011	.005	-.024	.035	.018	.073	-.011	-.071	.017
31	-.068	-.085	-.055	.045	-.079	-.021	.008	.033	-.073	.017
32	-.008	.048	.009	-.009	-.006	-.009	-.002	-.013	-.032	.020
33	.015	-.024	.045	-.127	-.012	-.077	-.004	-.046	-.024	.007
34	-.088	-.037	.063	.054	-.020	.060	.011	-.059	-.055	.046
35	.014	.029	-.060	.054	.011	.055	-.015	.048	.105	-.036
36	-.061	-.030	-.037	.092	.057	-.075	.014	-.062	-.044	.014
37	.003	-.063	.078	.001	-.015	-.075	-.032	-.085	.012	.029
38	-.027	.034	-.018	.036	.100	-.105	-.084	.008	-.033	-.006
39	.070	-.093	.024	-.148	-.064	.016	.001	.036	-.032	-.011
40	-.061	-.104	-.016	.050	.017	-.035	.004	-.079	-.027	.009
41	.035	-.032	.030	.076	.041	.010	.022	-.032	-.065	-.078
42	-.069	-.015	.040	-.007	.066	-.008	.036	-.033	-.087	.064
43	.041	.010	-.074	-.082	.005	.014	-.003	.045	.024	-.026
44	.036	-.033	-.064	-.070	-.015	.019	.038	.007	-.049	.019

APPENDIX D

"CONTINUED"

Questions	21	22	23	24	25	26	27	28	29	30
1	.058	.079	.029	-.034	.024	-.006	-.042	-.010	-.035	.053
2	-.077	-.129	.052	-.057	.021	-.038	.033	-.011	-.039	.022
3	-.029	-.049	-.131	-.082	.013	-.046	-.101	-.032	.024	.018
4	.032	-.080	-.061	-.074	.058	.003	-.035	-.019	.096	.050
5	-.022	.001	-.050	-.048	.102	-.010	-.045	-.007	-.003	-.041
6	.018	.087	-.017	-.054	-.007	-.034	-.005	-.024	-.014	-.092
7	.011	.025	.029	-.002	-.113	-.078	-.036	-.021	-.008	-.046
8	-.060	.024	.067	.063	.009	.015	-.023	-.014	-.097	-.049
9	.066	-.029	-.023	-.003	.083	.076	.025	.027	.092	.036
10	-.064	-.034	-.002	-.054	.053	.011	-.045	-.030	-.010	-.027
11	-.057	-.005	.022	-.021	.032	-.012	-.070	.044	-.036	-.071
12	-.008	.040	.002	-.007	-.019	-.009	.054	-.014	.052	-.011
13	.134	-.022	.013	.057	-.016	-.007	.031	.021	-.013	.005
14	.080	.052	-.099	.000	-.021	.017	.023	-.027	.134	-.024
15	.012	-.020	-.069	.074	.031	-.020	.012	-.007	-.042	.035
16	-.046	-.058	.062	-.085	-.099	.035	-.089	-.003	-.022	.018
17	.030	-.182	-.034	.003	-.003	-.030	.090	-.087	.047	.073
18	-.052	.021	.072	-.013	.073	-.034	-.084	-.063	-.020	-.011
19	.043	.061	-.057	.044	.001	-.037	-.029	.020	.028	-.071
20	-.034	-.012	.043	.043	-.029	-.063	.028	.085	-.054	.017
21	.666	.162	.037	.035	.009	.020	-.022	-.016	.080	.016
22	.162	.604	-.006	.027	-.036	-.045	-.083	-.017	-.011	-.057
23	.037	-.006	.555	-.029	-.051	-.029	.026	-.033	-.084	-.001
24	.035	.027	-.029	.656	.000	.028	.034	.010	-.191	.036
25	.009	-.036	-.051	.000	.741	-.027	-.064	-.115	-.030	-.037
26	.020	-.045	-.029	.028	-.027	.662	-	-.107	-	.054

							.118		.029	
27	-.022	-.083	.026	.034	-.064	-.118	.693	-.020	.009	.048
28	-.016	-.017	-.033	.010	-.115	-.107	-.020	.559	-.004	-.070
29	.080	-.011	-.084	-.191	-.030	-.029	.009	-.004	.629	-.059
30	.016	-.057	-.001	.036	-.037	.054	.048	-.070	-.059	.770
31	-.065	.028	-.039	-.050	.042	.092	.002	-.084	.005	-.010
32	.021	-.010	-0.000066	.040	-.029	-.018	-.016	-.129	-.081	.082
33	.046	.029	.064	.037	-.024	-.114	.113	-.006	-.046	.044
34	.099	.030	.048	.089	-.015	-.016	.136	.001	-.085	-.026
35	.079	.058	.003	-.005	-.019	.053	-.108	-.063	.022	-.050
36	.017	.013	-.161	.027	-.048	-.056	.035	.056	.045	.000
37	.003	.034	-.087	.082	-.005	-.054	.049	.022	-.001	-.019
38	.045	-.023	.014	.020	.054	.053	.003	.001	-.042	.155
39	-.027	-.082	.029	-.004	-.022	.042	-.094	-.040	-.049	-.041
40	.009	.054	-.022	.115	.030	.088	.045	.069	-.059	.116
41	.009	-.028	-.103	-.010	.026	.029	-.086	-.029	-.045	-.045
42	-.003	.012	-.092	.040	.027	.070	-.060	-.027	-.013	-.009
43	-.065	-.031	-.007	.038	-.028	.016	.000	.042	-.145	.013
44	.011	-.041	.067	-.135	.035	-.039	.013	-.022	.000	-.031

APPENDIX D

"CONTINUED"

Questions	31	32	33	34	35	36	37	38	39	40
1	.015	.032	-.040	-.069	.100	-.079	-.142	.057	-.056	-.004
2	-.126	-.061	-.026	.031	.004	-.023	-.006	-.082	.016	.021
3	-.008	-.006	.066	-.033	-.051	-.007	.021	.009	.004	-.062
4	.059	-.045	-.079	-.068	.004	-.084	.034	.000	.024	-.002
5	-.129	-.028	-.023	.017	.000	-.092	.015	-.050	-.027	.054
6	-.057	.029	-.036	.012	2.631E-05	.008	-.034	.025	-.020	-.049
7	-.005	.025	.039	-.086	.010	.056	-.053	-.023	-.072	-.019
8	.023	-.024	.025	-.015	-.019	-.040	-.028	.002	.124	-.025
9	-.029	-.052	.000	-.038	-.072	.002	.040	.096	-.025	-.005
10	.050	.003	.029	-.052	.011	.012	-.076	-.098	.028	.052
11	-.068	-.008	.015	-.088	.014	-.061	.003	-.027	.070	-.061
12	-.085	.048	-.024	-.037	.029	-.030	-.063	.034	-.093	-.104
13	-.055	.009	.045	.063	-.060	-.037	.078	-.018	.024	-.016
14	.045	-.009	-.127	.054	.054	.092	.001	.036	-.148	.050
15	-.079	-.006	-.012	-.020	.011	.057	-.015	.100	-.064	.017
16	-.021	-.009	-.077	.060	.055	-.075	-.075	-.105	.016	-.035
17	.008	-.002	-.004	.011	-.015	.014	-.032	-.084	.001	.004
18	.033	-.013	-.046	-.059	.048	-.062	-.085	.008	.036	-.079
19	-.073	-.032	-.024	-.055	.105	-.044	.012	-.033	-.032	-.027
20	.017	.020	.007	.046	-.036	.014	.029	-.006	-.011	.009
21	-.065	.021	.046	.099	.079	.017	.003	.045	-.027	.009
22	.028	-.010	.029	.030	.058	.013	.034	-.023	-.082	.054
23	-.039	-0.0000662	.064	.048	.003	-.161	-.087	.014	.029	-.022
24	-.050	.040	.037	.089	-.005	.027	.082	.020	-.004	.115
25	.042	-.029	-.024	-.015	-.019	-.048	-.005	.054	-.022	.030

26	.092	-.018	-.114	-.016	.053	-.056	-.054	.053	.042	.088
27	.002	-.016	.113	.136	-.108	.035	.049	.003	-.094	.045
28	-.084	-.129	-.006	.001	-.063	.056	.022	.001	-.040	.069
29	.005	-.081	-.046	-.085	.022	.045	-.001	-.042	-.049	-.059
30	-.010	.082	.044	-.026	-.050	.000	-.019	.155	-.041	.116
31	.584	-.021	-.070	.000	-.043	-.028	.017	-.030	.009	.103
32	-.021	.627	.016	.019	-.032	-.007	-.024	.083	-.071	.019
33	-.070	.016	.786	.049	-.036	.028	.034	-.053	-.002	.049
34	.000	.019	.049	.650	-.026	-.078	-.016	-.021	-.102	.048
35	-.043	-.032	-.036	-.026	.559	-.061	-.241	-.023	-.069	.004
36	-.028	-.007	.028	-.078	-.061	.571	-.001	-.007	-.023	.056
37	.017	-.024	.034	-.016	-.241	-.001	.553	-.104	.004	.008
38	-.030	.083	-.053	-.021	-.023	-.007	-.104	.764	-.042	-.030
39	.009	-.071	-.002	-.102	-.069	-.023	.004	-.042	.702	-.064
40	.103	.019	.049	.048	.004	.056	.008	-.030	-.064	.636
41	-.005	.013	-.085	.003	.037	.027	.018	-.038	-.095	.050
42	.029	-.048	-.047	.006	.001	-.041	.034	.018	-.045	.048
43	-.045	-.068	.011	.004	-.020	-.027	-.071	-.010	.089	.089
44	.074	-.143	-.003	-.108	-.031	.032	-.012	-.062	.025	.008

APPENDIX D

"CONTINUED"

41	42	43	44
-.090	-.067	.034	-.030
.037	.029	.058	.034
-.011	.050	-.035	.012
.015	.024	-.072	.025
.057	.079	.022	-.031
.007	-.065	.039	-.008
.081	-0.00004	-.072	.025
-.058	.029	.118	-.020
-.023	.027	-.009	-.013
.027	-.026	-.035	.039
.035	-.069	.041	.036
-.032	-.015	.010	-.033
.030	.040	-.074	-.064
.076	-.007	-.082	-.070
.041	.066	.005	-.015
.010	-.008	.014	.019
.022	.036	-.003	.038
-.032	-.033	.045	.007
-.065	-.087	.024	-.049
-.078	.064	-.026	.019
.009	-.003	-.065	.011
-.028	.012	-.031	-.041
-.103	-.092	-.007	.067
-.010	.040	.038	-.135
.026	.027	-.028	.035
.029	.070	.016	-.039
-.086	-.060	.000	.013
-.029	-.027	.042	-.022
-.045	-.013	-.145	.000
-.045	-.009	.013	-.031
-.005	.029	-.045	.074
.013	-.048	-.068	-.143
-.085	-.047	.011	-.003
.003	.006	.004	-.108

.037	.001	-.020	-.031
.027	-.041	-.027	.032
.018	.034	-.071	-.012
-.038	.018	-.010	-.062
-.095	-.045	.089	.025
.050	.048	.089	.008
.760	.034	-.054	-.082
.034	.819	-.014	-.083
-.054	-.014	.671	-.118
-.082	-.083	-.118	.642

APPENDIX E

THE STRUCTURE OF MBTI

The intent of this appendix is to briefly describe the history of MBTI and show the structure of MBTI. Personality theories have been around for decades. Allport (1937) portrayed two paths to study personality: the nomothetic psychology and the idiographic psychology paths. Nomothetic seeks to formulate a system of general laws that can be applied to different individuals, while idiographic attempts to achieve a unique understanding of a particular individual by investigating his/her facts or events. More recently, Maddi (1996) developed three models of personality: the consistency model, the conflict model and the fulfillment model. The following development of this dense field provides results from a preliminary scan of the literature on personality, trait theories, type theories, and cognitive theories as they are representative of some theories pertaining to the study of personality.

Carl Jung, a Swiss physician, wrote in his book (1921) "Psychological Type" that individuals behave in different ways, describing how we go and gather our information and make decisions and why individuals act the way they do. He developed what he called (basic psychological types): thinking, feeling, sensation, and intuition. Jung emphasized that "What is important in our natural inclination to either extraversion or introversion, combined with the four psychological types." [Kiersey, (1998), p.3]

At the same time, other studies and investigations took place with respect to the study of personality. Kiersey also suggested that these books, such as John Stewart's book in ethnology, in addition to Jung's Psychological Type's book, were placed in the background in the psychology field and left dormant for a long period. The commonly accepted reason is because at that time there was no motivation to pursue research toward the idea of human inborn differences. In other words, the whole idea of personality theory was neglected and left in a suspended state.

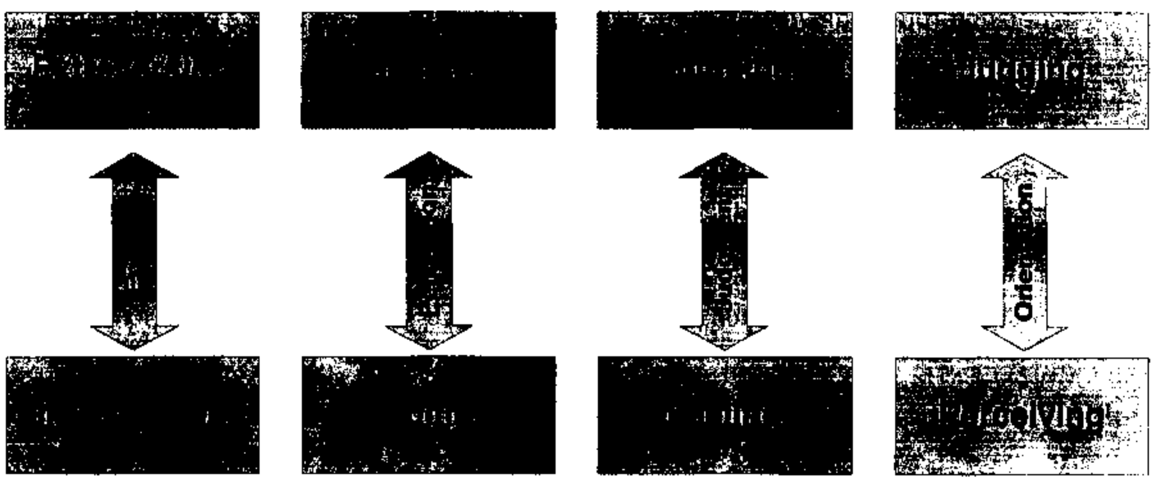
On the other hand, Jung's ideas were "given a new life almost by accident." [Kiersey, (1998), p. 3] Isabel Myers and her mother Kathryn Briggs were inspired by Jung's Psychological types (Myers, 1962; Myers & McCaulley, 1985). In 1962 they developed a questionnaire for identifying different kinds of personality. This questionnaire is called "The Myers-Briggs Type Indicator." The questionnaire is based on the theory of Jung's which is considered "one of the most comprehensive theories explaining human personality." [Turker and Kroeger, (2010), p.22]. This was further expounded by Saggino et al., (2000, p.1), who affirmed that MBTI "represents a major effort to capture the intricacies of Jung's (1971) theory of Psychological types." Thus, the MBTI has become a mainstay instrument for determining an individual's personality type.

The MBTI questionnaire is comprised of 70 questions and it was designed to identify sixteen patterns of actions and attitude. The MBTI consists of four scored scales to measure the following eight preferences:

- Extraversion (E)-Introversion(I),
- Thinking(T)- Feeling(F),
- Judging(J)-Perception(P),
- And finally Sensing(S)-Intuition(I).

The MBTI construct consists of 4 main dichotomies (8 categories): "each of the four dichotomies are broad and multifaceted rather than narrow and unidimensional" [Quenk, (2009), p.5]. The *Extraversion-Introversion* dichotomy describes energy utilities. The second dichotomy, *Sensing-Intuition,* describes perception. The third dichotomy, *Thinking-Feeling,* describes judgment and the last dichotomy, *Judging-Perceiving,* describes orientation. Figure E 1 displays the MBTI 8 categories scale (4 dichotomies) and their facets.

Figure E 1: MBTI Eight Categories



APPENDIX E

MAPPING THE SYSTEMS THINKING CHARACTERSITICS TO THE MBTI

This appendix provides input for future research. It is important to mention that the mapping process does not validate the systems thinking instrument in any way. In the mapping phase, each systems thinking characteristic (7-Sc) was scaled and mapped to the Myers-Briggs Type Indicator (MBTI). Each systems thinking characteristic was assessed through administration of approximately 14 questions with two answer choices. This research adopted David Keirsey and Marilyn Bates' questions (1978) for classification of the MBTI for individuals, which included 70 questions. Four dichotomies with eight categories were used in the mapping process.

Table F1 provides the results of the mapping process for each of the 7 Sc characteristics to the eight categories of MBTI. For example, "interconnectivity" as the first systems thinking characteristic was mapped to 14 questions from the MBTI. The second and third columns respectively display the questions that have been mapped to 2 Sc characteristics or 3 or more Sc characteristics.

Table F 1: Mapping Process

Systems Thinking Characteristics	MBTI-Mapping Questions	Shared-Questions 2SC	Shared-Questions 3SC
[redacted]	[redacted]	[redacted]	[redacted]
Identify and understand the purpose of integration.	1,11,12,29,36,43,50,64, 1,8,64		
[redacted]	[redacted]	[redacted]	[redacted]

Table F 1: Continued

Provide inputs to identify new risk behaviors and areas where changes need to be considered.	15,36,57		
Possess interdisciplinary knowledge.	44, 66		
Pay close attention to the interactions and interdependencies among the systems from a holistic viewpoint.	8,15,44.61,57,66		
Coordinate (teamwork), communicate (sharing data and information), and work closely (with other heterogeneous systems) to achieve the overall purpose.	1,11,12,29,36,43,50,64, 1,8,64		
Autonomy	6,18,28,33,41,47,60,67	28,47,	
Appreciate and embrace autonomy.	41,47,6,60,18		
Draw the difficulties autonomy brings to complex problem domain.	28,18		33,60,67
Balance the tension between autonomy and integration.	28,33,47,67		
Possess the ability to bargain and negotiate to address complex systems objectives.	6,33,47,67		
Evolutionary Development	14,15,20,[illegible] 21,27,30,34,35,37,39,42, 45,48,55,56,62,63,70	15,39,48,55	
Trace and map the ongoing change in needs, technology, and social infrastructure.	15,35,21,34,48,55,56,70		
Focus on the whole instead of the sequential traditional treatments (life cycle).	20,34,35,27,35,37,39,42 ,48,55,70		14,20, 21,27,30,34,35,3 7,42,45,56,62,63, 70
Take relevant multiple perspectives into consideration.	20,27,39,48,70		

Table F 1: Continued

Explore the environment and look for new-outside opportunities to deal with the pace growth of complex systems.	15,34,35,[illegible],42,45,48 ,56,63		
Have the ability to distinguish between the SoS need and the system aggregation need.	35,48		
Be able to formulate rapid shifting solutions.	14,34,42,62		
Emergence	2,3,7,9, 13,14,16,17,20,21,22,24, 27,34,35,37,38,42,44,45, 48,49,51,56,58,62,63,65, 66,69,70	3,7,9,13,48	
Identify and inspect all aspects (non-technical) of the problem.	2,7,13,17,35,45,48,58,6 3,70		
Explore the environment to deal with emergence.	2,9,13,20,22,27,42,63		
Think in a holistic way [illegible] and avoid obsession with details. [illegible]	[illegible] 44,49,51,66,69 [illegible]		2,14,16,17,20, 21,22,24,27,34,3 5,37,38,42,44,45, 51,56,58,62,63,6 5,66,70
Prepare by designing for flexibility and adaptability in the system.	9,20,22,27,34,42,45,62		
Appreciate the high level of uncertainty.	3,16,17,20,27,37,42,48, 56,62,65,69		
Avoid optimal solution and consider a range of satisficing solutions.	14,20,27,45,62,63		
Complexity [illegible]	2,10,14,16,[illegible]24, 27,28 [illegible] 45,46,51,53,55, 56,62,63,65,66	3,23,28,39,46,53 [illegible]	
Appreciate and assess the degree of complexity (no full control).	2,14,20,27,28,30,31,42, 44,56,65		

Table F 1: Continued

Have ability to distinguish the characteristics of complex system problems and understand the limitations of TSE.	14,16,20,24,27,35,42,51		14,16,17,20,24,27,30,34,35,38,42,44,45,51,56,62,63,65,66
Identify and address the external influences that constrain the complex problem domain.	30,34,38,45,46,53,55,62,65,66		
Be able to align between the nature of the problem, the methodology taken and context where complex systems operate.	17,23,34,39,46 [illegible]		
Grasp multidisciplinary problems.	10,16,24,35,45,53,62,63		
Holistic Paradigm [illegible]	2,3,16,[illegible]20,[illegible]24,27,30,34,[illegible]48,51,58,59,60,6[illegible],66,67,69,70	3,23,59 [illegible]	
Recognize holism as a new paradigm of thinking.			
Identify and assess all aspects of the problem.			2,16,17,18,20,24,27,30,34,37,38,42,44,48,51,58,60,65,66,67,69,70
See the big picture and understand the system as a whole unit.			
Focus on the whole and avoid looking at the tiny detail.	[illegible]		
Demonstrate understanding of the laws and principles relevant to the problem under study.			
Treat the problem as a whole and avoid thinking in 'cause and effect' paradigm.			

Table F 1: Continued

Flexibility	2,4, 5, 7,9,11,13,18,19,21,22,25,26,32,33,40,43,45,46,47,50,52,53,54,58,59,60,61,63,64,67,68,70	7,9,11,13,32,33,43,46,47,50,53,59,61,64,68	
Appreciate the importance of flexibility and adaptability as functions to deal with emergence and uncertainty.	7,9,11,13,18,70		2,18,21,22,33,45,58,60,63,67,70
Recognize the importance of having a flexible design to add, adjust or remove any of the systems' components.	19,21,22,25,26		
Remain open to all ideas.	32,33,40,43,45,46,47		
Encourage to dissemination of plans and idea.	50,52,53,54,58		
Possess ability to accommodate any changes or modifications in ensemble systems.	59,60,61,63,64,67,68		

VITA

Teaching Interests

Global Supply Chain & Critical Infrastructure, Systems Design and Analysis, Engineering Management, Systems Dynamics, Risk Management, Integrated Systems Engineering, and logistics

Research Interests

The main focus of my research is to develop multidisciplinary methods and tools to provide individuals and organizations with capabilities to more successfully navigate the complex system problems characteristic of the 21st Century. The Instrument that I have developed has a strong interest in multidisciplinary research to integrate technical, social, and managerial aspects into designing solutions to organizational problems from different fields (healthcare, transportation systems and others). Other research interests include team dynamics and group decision making and performance, and critical infrastructures.

Education

Jan'09 – Present **Ph.D., Engineering Management and Systems Engineering**, Engineering Management & Systems Engineering Department, Frank Batten College of Engineering & Technology, Old Dominion University, Norfolk, VA

- Advisor: Prof. Charles B. Keating
- Dissertation title "A new systems thinking tool to assist individuals navigating the organizational problem domain"
- Dissertation Committee Chair: Professor Chuck Keating

Sept '03 – June '05 **Masters, Operations Management and Research**, Business Administration Department, College of Economics and Administrative Sciences, The Hashemite University, Zarqa, Jordan

Oct '99 – June'03 **Bachelors, Business Administration/Finance**, Business Administration Department, College of Economics & Administrative Sciences, The Hashemite University, Zarqa, Jordan

Teaching Experience

Jan '11 – Present **Instructor,** ENMA 301 Introduction to Engineering Management, ENMA 415 Introduction to Systems Engineering, ENMA 420 Statistical Concepts in Engineering Management, and ENMA 302 Engineering Economics, Engineering Management & Systems Engineering Department, Old Dominion University.

Jan '09 – Present **Graduate Research and Teaching Assistant,** Engineering Management & Systems Engineering Department, National Centers for System of Systems Engineering (NCSOSE), Old Dominion University.

- Engage in scholarly publication and presentation to peer groups at conferences and seminars.
- Develop materials for courses offered in the Navy graduate students program.