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**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

THESIS

**INCORPORATING LEARNING THEORY INTO EXISTING
SYSTEMS ENGINEERING MODELS**

by

Valentine Leo

September 2013

Thesis Advisor:
Co-Advisor:

Gary O. Langford
Douglas Nelson

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**INCORPORATING LEARNING THEORY INTO EXISTING SYSTEMS
ENGINEERING MODELS**

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

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ABSTRACT

Systems engineering and learning theories are two major disciplines that involve preparing people to solve problems. While learning theories and their elements are apparent in the field of systems engineering, limited work has been performed on the interactions and relationship between these two disciplines. This thesis aims to establish and discuss a relationship between systems engineering and learning theories over the key phases of a systems life cycle. This thesis discusses how organizations can use the information attained from the collaborative approach between systems engineering and learning theories to leverage practitioners' work quality, capability, and decisions to help justify and improve key systems parameters.

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LIST OF ACRONYMS AND ABBREVIATIONS

CIA	Central Intelligence Agency
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
INCOSE	International Council on System Engineering
MOP	Measure of Performance
NASA	National Aeronautics and Space Administration

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EXECUTIVE SUMMARY

Evident in the life cycles of most systems are the concepts of systems engineering and learning theories. This thesis aims to relate both systems engineering and learning theory to illustrate how knowledge is attained, learned and retained through various forms of learning and its associated activities. Proper characterization and utilization of these learning forms may be used to enhance the effectiveness and efficiency of systems engineering activities during the systems life cycle.

A systems' life cycle spans conceptualization to requirements and development; and to operations and support to disposal, involving multiple stakeholders and different activities. Established Systems engineering methodologies have been applied to aid systems engineers in systematically and holistically approaching system issues in any phase.

Regardless of phases in the system's life cycle, the three primary parameters that stakeholders focus on heavily are cost, performance, and schedule (Forsberg & Harold, 1992). Most systems engineering methodologies accept inputs and assessments from various phases in the system's life cycle, which can later be extrapolated into these domains of interest.

Since a system's life cycle can be perceived as a collection of activities and phases involving stakeholders, it is apt that learning theories can be introduced and incorporated into the systems engineering approaches applied to show that there is relation between the two disciplines. The output as well as tradeoffs of these collaborated methodologies shall be visible in the three key parameters of concerns—cost, schedule and performance. This thesis aims to discuss how the information and relationships of the two disciplines can be used to improve key parameters via systems engineering activities.

Development of learning theories in relation to systems engineering approach within organizations can be validation in the future and explored further in future research.

LIST OF REFERENCES

Forsberg, K. & Harold M. (1992). *The relationship of systems engineering to the project cycle*. Engineering Management Journal, 4(3), 36–43.

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I. INTRODUCTION

A. OVERVIEW

With a history dating back to the 1950s, Systems Engineering and its applied methodologies can be found in multiple disciplines, both within the defense and civilian communities (Marvel, 1997; Goode 1957). Systems engineering as defined by International Council on Systems Engineering (INCOSE), “Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem,” has direct impact on the life cycles of systems in several domains, impacting- the key parameters on cost, performance, and schedule (Forsberg & Harold, 1992). These factors as highlighted by (Forsberg & Harold, 1992) are closely linked to stakeholders’ requirements, constraints, and boundaries.

Systems engineering is traditionally viewed as an approach assumed to be executed by a systems engineer through the executions of systems engineering methods, approach, and use of systems engineering tools (Langford, 2013).

Human based organizations being dynamic and organic are exposed to the learning element of learning theory as they operationalize learning in carrying out their tasks. The existence of learning theory and its application have been documented for 2000 years. These theories encompass the domains associated with social and cognitive psychology and philosophy (Illeris & Knud, 2004).

The aim of this thesis is to quantify, qualify and explore the possible integration of various learning theories in conjunction with systems engineering methodologies when applied during the life cycle of a system. Methodologies in

this context refer to the “HOW” each task is carried out as defined in the “Survey of Model Based Systems Engineering Methodologies” by INCOSE (2008).

A Method (M) consists of techniques for performing a task, in other words, it defines the “HOW” of each task. (In this context, the words “method,” “technique,” “practice,” and “procedure” are often used interchangeably.) At any level, process tasks are performed using methods. However, each method is also a process itself, with a sequence of tasks to be performed for that particular method. In other words, the “HOW” at one level of abstraction becomes the “WHAT” at the next lower level.

1. Questions

When looking at the life cycle of a system, the use of Systems Engineering approach and elements of learning theory can impact key parameters; this thesis investigates the following questions:

- How effective are the existing methods of applying systems engineering to system life cycle problems?
- How accurate are the existing methods of learning when applied to life cycle of the system?
- Which elements of learning theory apply in the life cycle of systems?
- To what extent are elements of learning theories applied and used with Systems Engineering approach?
- How will the system differ in terms of key performance parameters after elements of learning are introduced along with Systems Engineering approach?
- How will the stakeholders benefit from the incorporation of elements of learning theory in the Systems Engineering approach?

2. Hypothesis

This thesis begins with establishing two driving hypotheses, namely:

a. Hypothesis #1

Application of systems engineering methods can be used to improve the key parameters of a system during its life cycle.

b. Hypothesis #2

Information attained from using learning theory's framework when looking at systems engineering activities can be utilized to improve key parameters.

3. Motivation and Background

Previous studies have investigated the details and benefits of Systems Engineering methodologies and learning theory, as well as how they impact projects and organizations. However, these studies were performed independently within their respective domains.

Boarder (1995) identified through his work the outline of a model-based generic systems engineering process that can be applied to various disciplines and industries. The benefits and advantages of systems engineering application had been discussed by several researches across a broad spectrum of disciplines (Frederick, 2007; Frank, 1995; Barker, 2003).

Independently, learning theory has been researched extensively on its interactions within an organization, with vast concentration on the psychological, educational, philosophical, social and cognitive domains (Grusec, 1992).

The gap between systems engineering and learning theory has not been explored either qualitatively or quantitatively until now. That being said, we lack the vision to see how these two disciplines affect each other, and in our case, affect each other throughout the life cycle of a system.

Work and research has, however, been documented on the learning curves of systems engineers as professionals; deSouza (2008) identified that one of the contributors to the performance of a systems engineer is the work experience of the systems engineer. deSouza (2008), also highlighted that the work experience of a systems engineer increases, the better the work performance delivered.

To benefit the various key parameters that may be seen in the life cycle of any system as well as meet the stakeholders' requirements, there is a need to understand the interactions between elements of learning theory and activities in the systems engineering approach Appendix A (Langford, 2013). The graphical representation of the overlapping of these two major domains can be seen Figure 1.

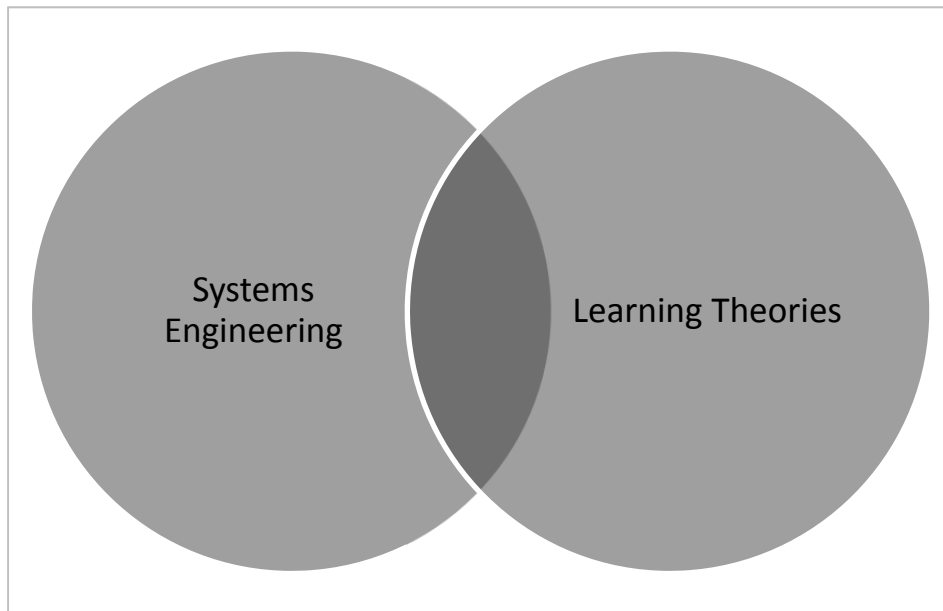


Figure 1. Relationship between systems engineering and learning theory.

The focus of this thesis will be concentrated in the overlapping region. This thesis will relate, characterize and apply the Information found in the overlapping regions.

B. APPROACH OF THESIS

A qualitative approach was used to acquire and manage the information for the analysis performed in the course of this thesis, this will be covered in detail in Chapter V. Evaluation and analysis of data was performed via the use of qualitative tools. The qualitative approach was intended to interpret the current

research on systems engineering methodologies and learning theories, in particular, their contributions and benefits.

The quantitative approach in this thesis was used to investigate mathematically the relationships between the two major domains of systems engineering and learning performed on the relationships between the two major disciplines; systems engineering and learning theory.

The overview of the thesis's activities covers history, analysis and idea integration; hierarchically represented in Figure 2.

A systems engineering approach was used in the process of establishing this thesis, particularly in the consideration of the types of activities, their interactions and relationships required in the generation of the thesis. The inputs and outputs throughout each phase of the thesis follow closely the iterative approach adopted during systems engineering methods.

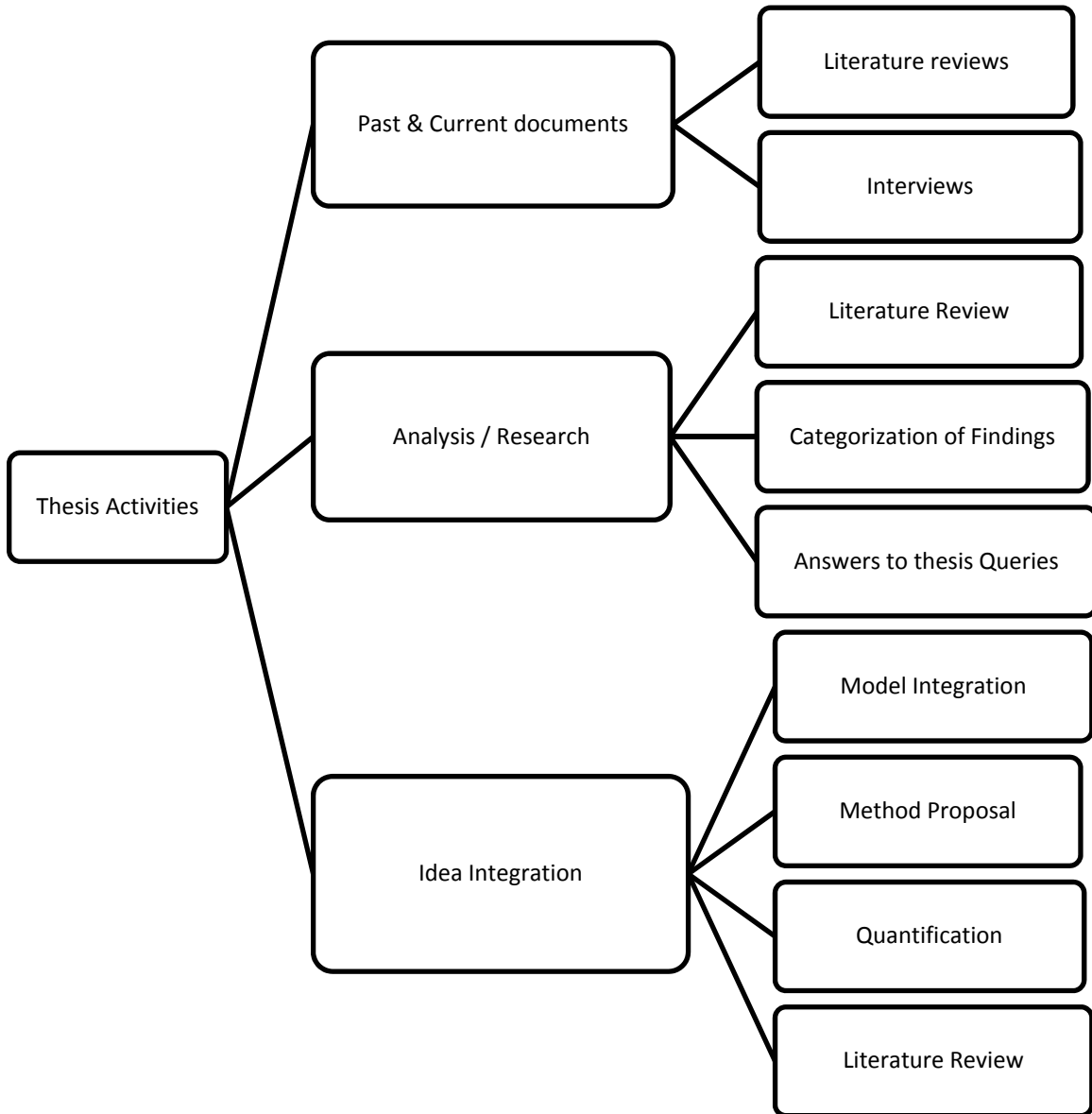


Figure 2. Hierarchical overview of thesis methodology

Compartmentalizing the approach of this thesis in the above manner also allowed for a systematic and clearer form of information gathering and presentation.

There will be three main categories of work performed during the course of this thesis. First, there will be the sourcing of information, where the gathering of important and useful data is performed via literature reviews and interviews.

Second, the gathered information will be analyzed and reviewed in details, and eventually framed to fit for use in this thesis. This is done mainly so through categorization of the literature and findings. Finally, upon the characterization of the gathered information, ideas and concepts will be generated and explored. The core of this thesis lies in this section, where ideas are proposed, integrated and justified.

The purpose of this overview is to allow the reader to understand and better follow through the thinking process during the development of this thesis.

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II. LITERATURE REVIEW

After some initial groveling, know what you are looking for. Approach the literature with questions and remember that your goal is to advance it, not simply to marvel at its wonders. Seek an appropriate balance between appreciation and advancement of the literature. (Marx, 1997, as cited in Silverman, 2005)

A. METHODOLOGY OF LITERATURE REVIEW

Literature review can be seen as the gathering of information and data attribution to the contents of the thesis. The above quote by Marx (1997) reinforces the importance of not only sourcing critical literature reviews but also the importance of advancing on the existing and past works. Essentially, the sources of literature reviews can come in many forms. Figure 3 shows the various means of attaining information, allowing comprehensive and updated insights from various resources.

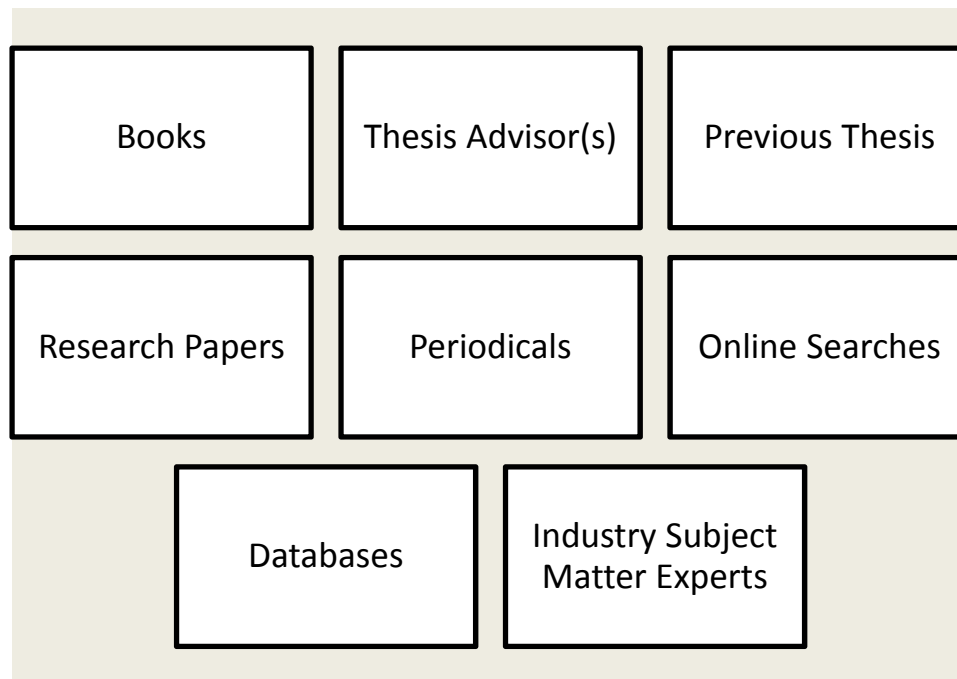


Figure 3. Sources of information and data.

B. SYSTEMS ENGINEERING APPROACH

1. Definition of Systems Engineering

Documented in previous papers and researches are a variety of definitions pertaining to the term systems engineering, among them a discipline of study or application of processes. INCOSE (2004) has a definition of systems engineering as

..an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.

NASA (2007)¹ highlighted the multidisciplinary process approach of systems engineering as follows:

Systems engineering is the art and science of developing an operable system capable of meeting requirements within often opposed constraints. Systems engineering is a holistic, integrative discipline, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, human factors engineers, and many more disciplines are evaluated and balanced, one against another, to produce a coherent whole that is not dominated by the perspective of a single discipline.

The definition of systems engineering as provided by INCOSE and NASA can be summarized and paraphrased as having a holistic view of a system and their stakeholders throughout the system's lifecycle.

¹ Comments on systems engineering throughout Chapter II are extracted from the speech "Systems Engineering and the Two Cultures of Engineering" by Michael D. Griffin, NASA Administrator.

2. Systems Engineering and Project Management

Often overlapping, systems engineering is seen to be closely associated with project management and control (Sage and Armstrong, 2000). NASA (2007) represented this association as shown in Figure 4. Derived stakeholders interest from these two aspects collectively can be identified to be cost, performance, and schedule; often in the form of stakeholders' requirements and constraints.

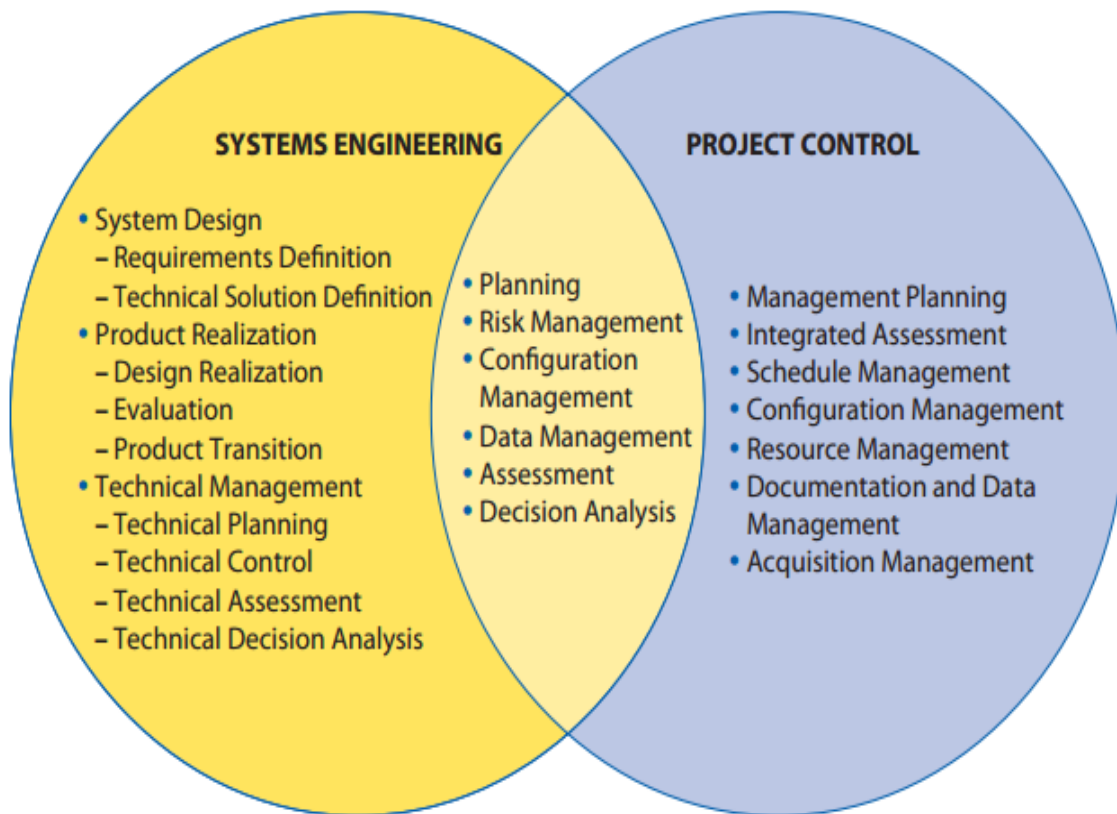


Figure 4. Systems engineering and project management

Although this form of systems engineering and project management grouping will not be explicitly used in this thesis, it will be useful as it helps put in perspective the required activities that can be used as a reference for later chapters in this thesis. In this thesis, the systems engineering activities pertaining to system design, product realization, and technical management are being

highlighted in later chapters. In project management, activities such as management planning, resource management and acquisition management is being highlighted in this thesis. Overlapping elements such as planning, decision analysis and assessment will be used as well.

3. Life Cycle of Systems

As most projects involve systems comprising of multiple disciplines, through the systems life cycle, it is beneficial to the stakeholders that an approach which possesses a variety of disciplines be applied. The systems engineering approach is such an approach.

The life cycle of a system with reference to the Department of Defense Architecture Framework's (DoDAF) defense acquisition management system encompasses the requirement phase to operations phase as represented in Figure 5.

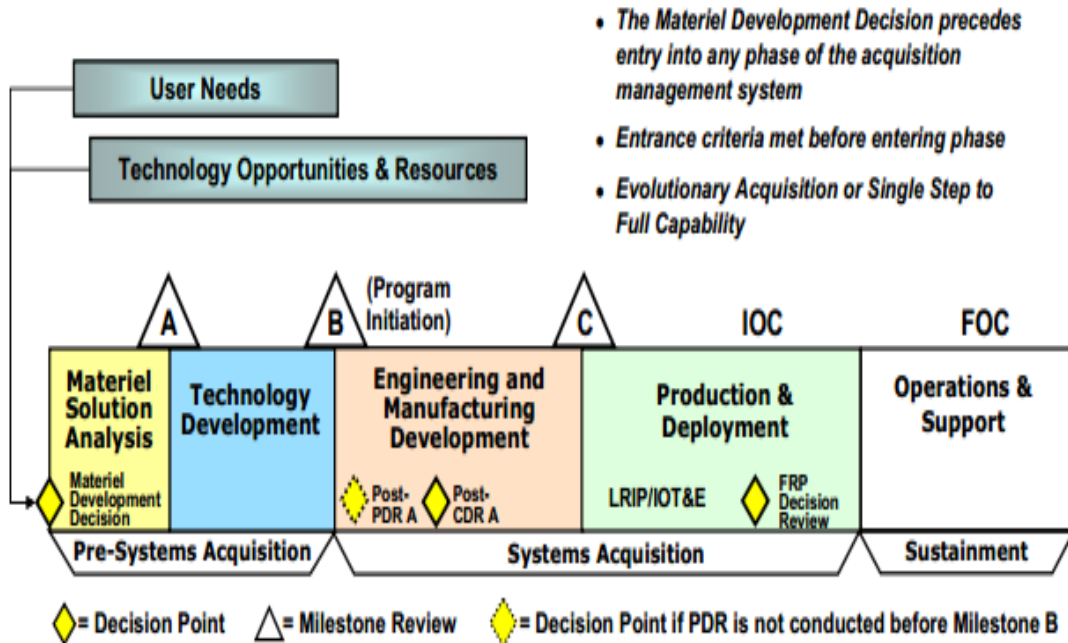


Figure 5. Defense acquisition management system (From DoDAF Acquisition Guidebook, 2011)

As shown in Figure 5, the sub-phases of each phase in the defense acquisition management model can be classified into three main phases, namely

- Pre-systems acquisition
- Systems acquisition
- Sustainment

However, in the context of this thesis, the phases of pre-systems acquisition shall be decomposed into project definition, requirements definition, analysis, and design. The phase of prototype build, verification, and disposal was also introduced and included in the system's life cycle. The complete life cycle of a system is as shown in Figure 6.

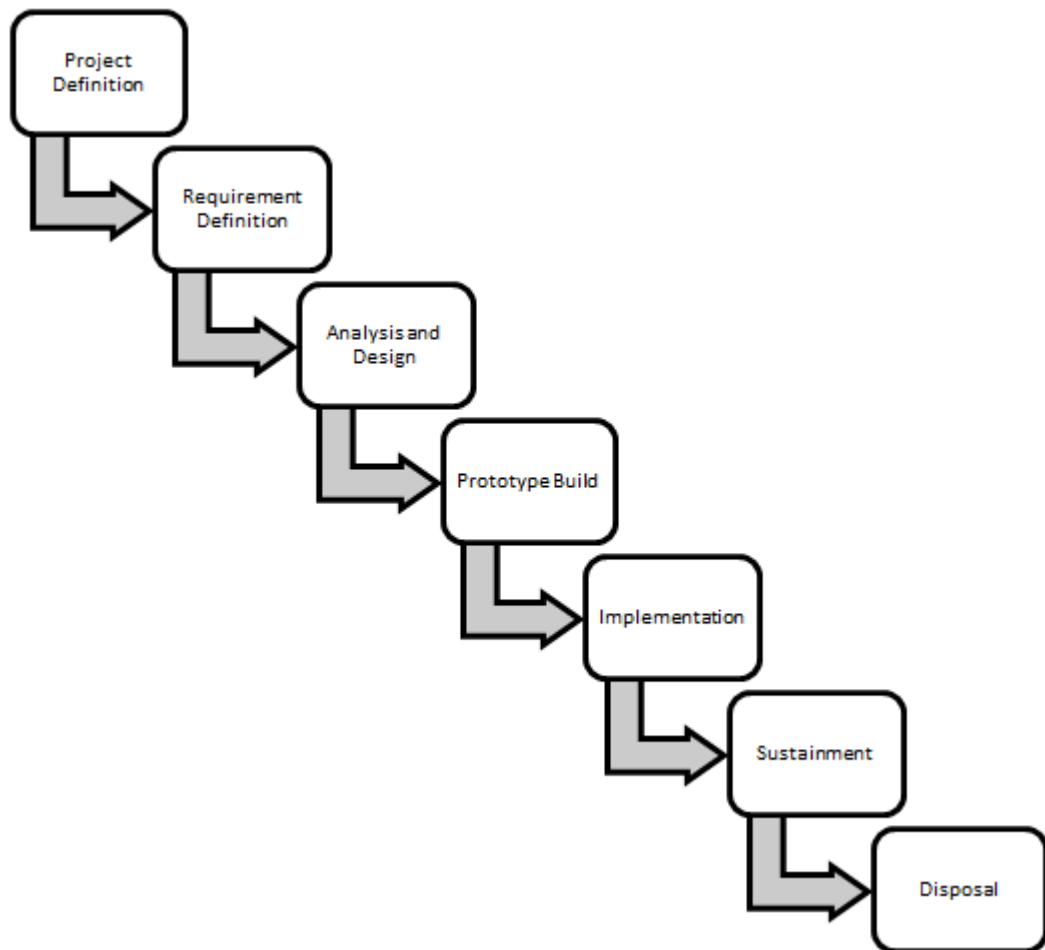


Figure 6. General life cycle of a system

Although this life cycle may differ from system to system, the above life cycle puts in perspective the general main phases of a systems life cycle. These phases will appear in later chapters of this thesis to illustrate the relationship between learning and systems engineering activities.

4. Systems Engineering Methodologies

The systems engineering process mentioned in the previous section serves as a guide for the flow of work managed by the acquirers, developers, and operators of the system. The proper management of the process requires a method. Turner (2009) defines a method as

...a collection of inter-related processes, practices, artifacts, agents, resources and tools. A method is essentially a "recipe." It can be thought of as the application of inter-related processes, practices and tools wherein different agents use resources to create and apply artifacts to a class of problems.

INCOSE (2008) identified the definition of methodology as

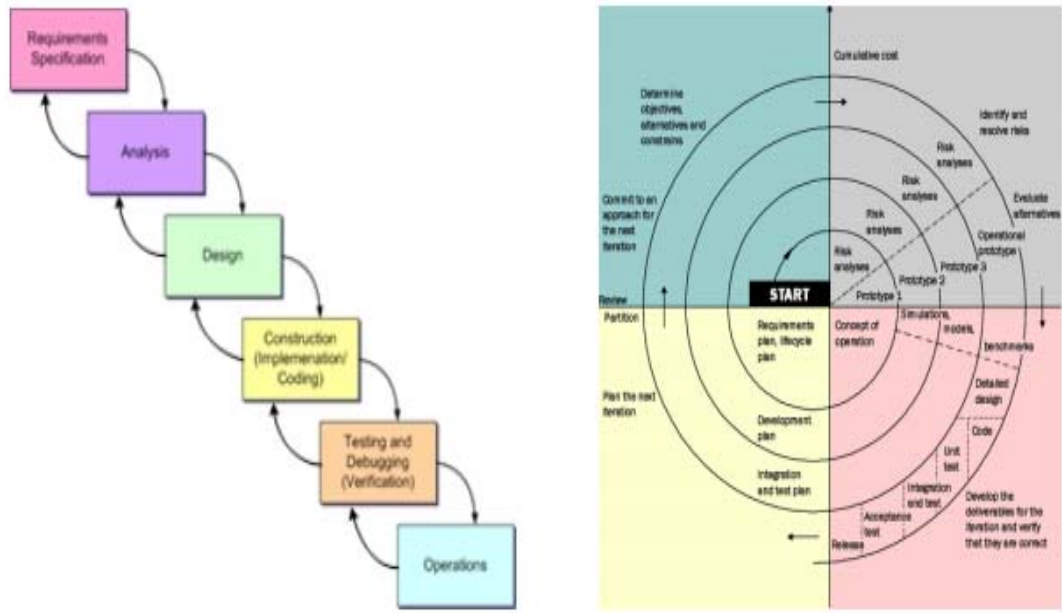
...a methodology is essentially a "recipe" and can be thought of as the application of related processes, methods, and tools to a class of problems that all have something in common.

However, there are inconsistencies between the 2 definitions from INCOSE and Turner. The definition of method as defined by Langford (2013) shall be adopted throughout this thesis.

Langford (2013) defined a method as:

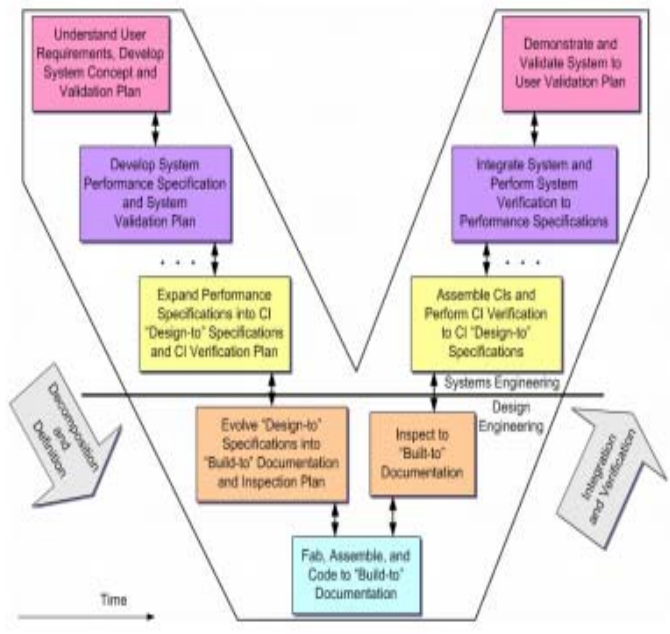
Method is the systematic, orderly, and logical way of doing something.

INCOSE (2008) identified that all systems engineering methods applied in projects across the government, industries and academia can be classified into three seminal models. They include: 1) waterfall model (Royce, 1970); 2) spiral model (Boehm, 1988); and 3) "Vee" model (Forsberg & Moog, 1992) as illustrated in Figure 7.



(a)

(b)



(c)

Figure 7. Seminal lifecycle development models: (a) Waterfall, (b) Spiral, (c) "Vee" (From INCOSE, 2008)

5. Benefits of Applying Systems Engineering Methodologies

Previous researches and studies performed on case studies positively showed the benefits to various project stakeholders when the application of the systems engineering process is evident. Using both qualitative and quantitative approaches, Honours (2004) summarizes in his paper that an effectively applied systems engineering process offers benefits in the cost, quality, and schedule domains when handling large scale projects.

Kludze (2004) identified in his paper a survey of staff from NASA and INCOSE that shows the overall and cost benefit impacts of systems engineering on projects; results of this survey are shown in Figures 8 and 9, respectively.

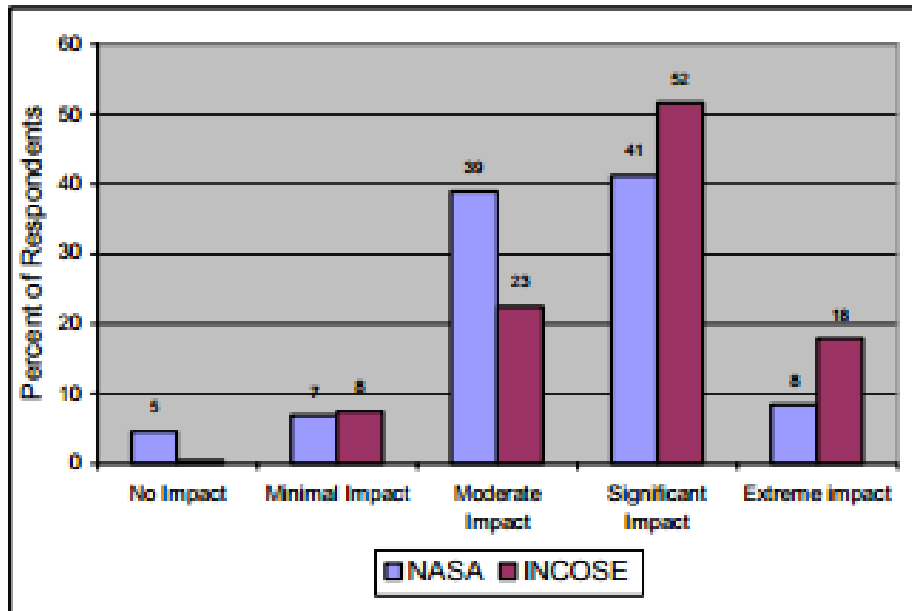


Figure 8. Survey of overall impact of SE on projects (From Kludze, 2003)

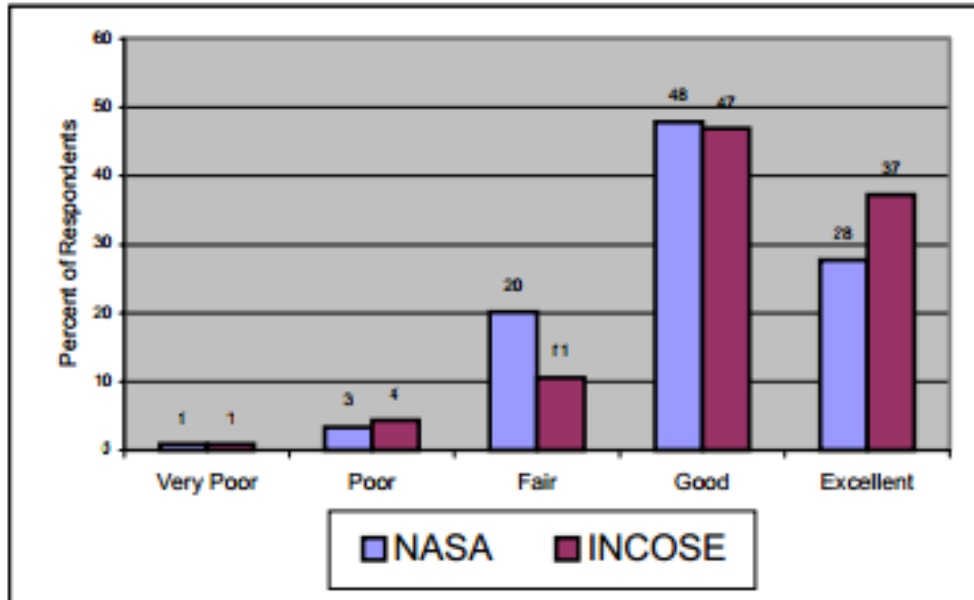


Figure 9. Cost benefits of systems engineering (From Kludze, 2003)

Kludze (2004) also identified in his paper the benefits of systems engineering in terms of improving technical performance; the results of that survey are shown in Figure 10.

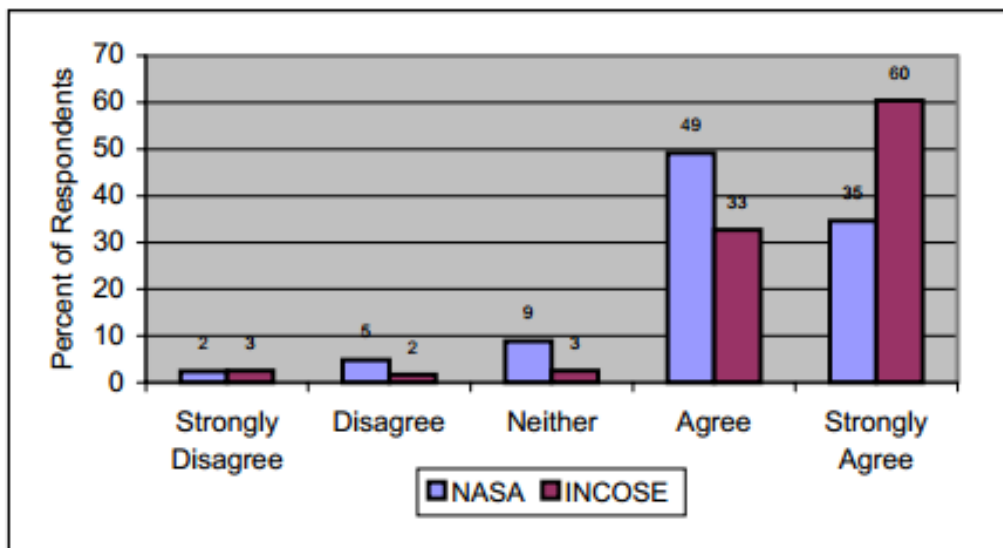


Figure 10. System engineering enhancing technical performances (From Kludze, 2004)

6. Loss Function

Relating losses in the form of Energy, Matter, Material Wealth, information against performance as defined by Langford (2012) is known as the loss function; quantifying the benefits achieved by variability reduction around the system performances, allowing for justification of decisions undertaken by decision makers (Choi & Langford, 2009).

These decisions may be resources, designs; Taguchi (1990) identified 3 major types of quality loss functions; namely smaller-the-better (STB), larger-the-better (LTB) and nominal-the-best (NTB). The application of each type of loss function strategies used is based on either the “buyer” or the “seller” requirement towards performance (Langford, 2012).

In later sections of this thesis, the combination of all three STB, LTB and NTB loss functions, otherwise known as the generalized loss function, will be used in the quantifying phases of this approach. This is graphically represented in Figure 11.

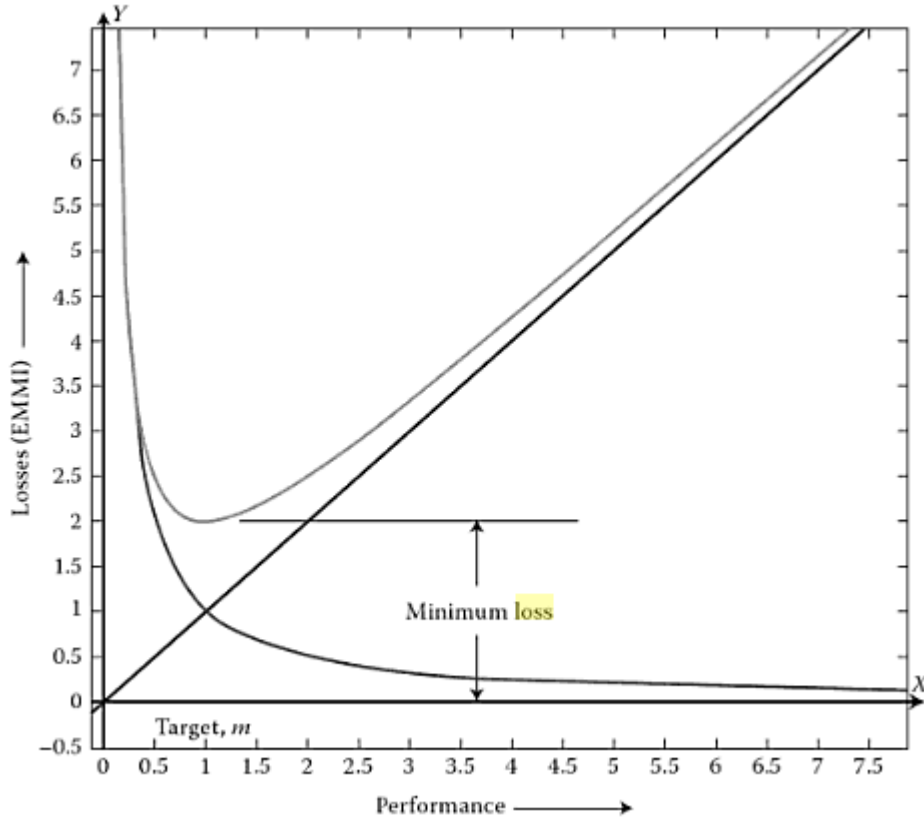


Figure 11. Generalized loss function relating performance to quality (From Langford, 2012)

In short, the loss function measure quality loss against performance based on inputs from parameters and quality response.

A mathematical way to interpret the generalized loss function (L_n) is as shown below (Choi and Langford, 2009):

$$L_n(x) = -2 C_s m^n + C_s x^n (1 + m^{2n} x^{-2n}) \quad \text{Equation 1}$$

where:

L_n = expected loss function

C_s = proportionality constant

m = quality response

n = the shape parameter

C. LEARNING THEORIES

1. Definition of Learning

Documented in previous past papers and researches are a variety of definitions pertaining to the term “learning.” Ambrose et al. (2010), defined learning;

Learning is a process, not a product. However, because this process takes place in the mind, we can only infer that it has occurred from students’ products or performances.

Learning involves the change in knowledge, beliefs, behaviors, or attitudes. This change unfolds over time; it is not fleeting but rather a lasting impact on how the students think and act.

The process of learning takes place not only under the umbrella of teaching, it can occur anywhere, anytime, and to anyone; as well as in the context of systems engineering processes. For this thesis, the learner, who can be any one of the stakeholders, shall be known as the “student.”

2. Types of Learning Theories

An overview of the classification of learning theories as identified by Lepi (2012) is shown in Figure 12. These theories can be broken down into two major groups, internal and external, which are later further decomposed into sub-groups. Internal comprises of mental and physical learning aspects, whereas the external forms of learning theories includes personals and environmental elements. This form of characterization helps the learning theory practitioner to further analyze and understand how learning takes place with respect to a person and his environment.

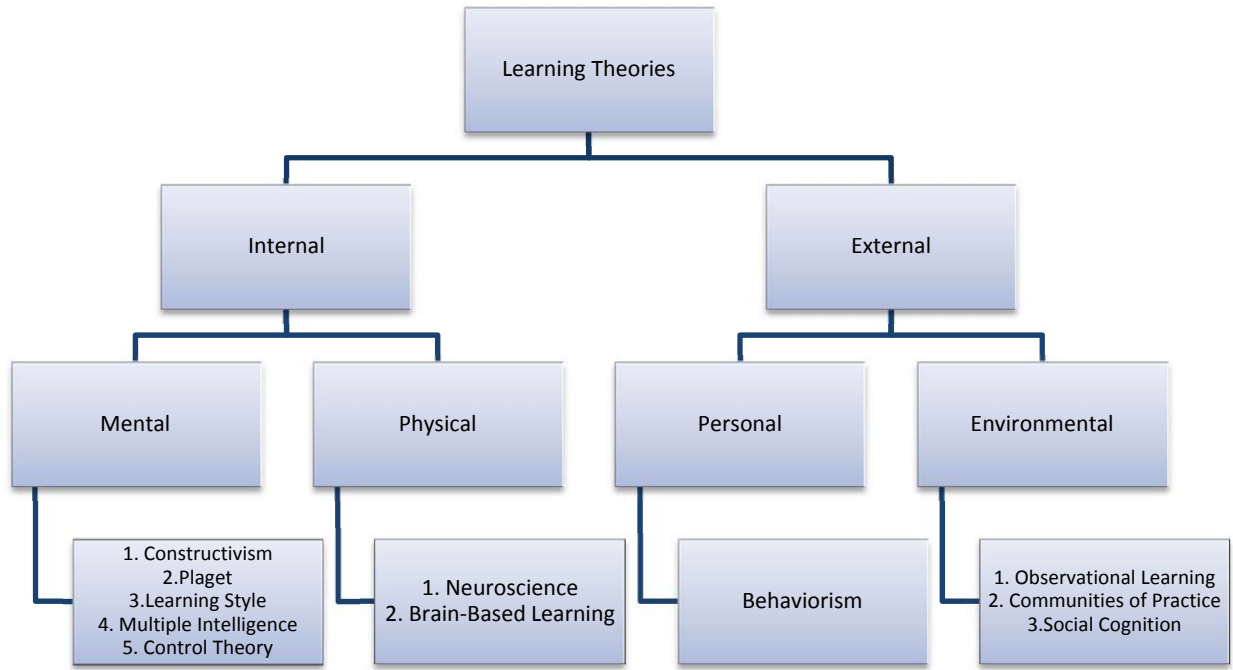


Figure 12. Overview of learning theories

From a functional perspective, learning theories till date can be summarized and categorized into four main areas, namely Behaviorism, Cognitivism, Constructivism, and Connectivism. A simplified representation of Lepi's (2004) work on the definition and means of the four types of functional learning theories can be summarized and seen in Table 1.

Table 1. Classification of learning theories

	Behaviorism	Cognitivism	Constructivism	Connectivism
Definition	Learning is a process of reacting to external stimuli	Learning is process of acquiring and storing information	Learning is a process of construction subjective reality base	Learning is a process of connecting specialized nodes or information sources
Types of learning	Task-based	Reasoning, clear objectives, Problem solving	Socially	Distributed within a network.
How	Understand and Remember	Create and Evaluate	Analyze and Apply	Recognize and Connect

These four main categories allow practitioners of learning theories to conduct in-depth studies and assessments pertaining to learning theories with better accuracy and resolution.

In the context of this thesis, the above categories were used to establish a basis for how the stakeholder(s) attain their knowledge pertaining to and from the activities involved in the systems engineering process.

3. Using Learning Theories

Learning theories by themselves bear no direct qualitative or evidentiary benefits, however researchers and educators can use frameworks (Langford, 2013) derived from these theories to analyze individual learning styles and develop learning activities targeted to the specific learning styles of their students. This enhancement of learning methods takes place in the several forms, such as education, environment, mentoring, and demonstration.

It is common that learning theories overlap. Lepi (2012) recognized that overlapping may occur along with the relevance of connectivism. In this thesis, we viewed the element of the many aspects of learning as a whole element. Lepi (2012) identifies the relationship between the various forms of learning as complete learning theory, as represented in Figure 12.

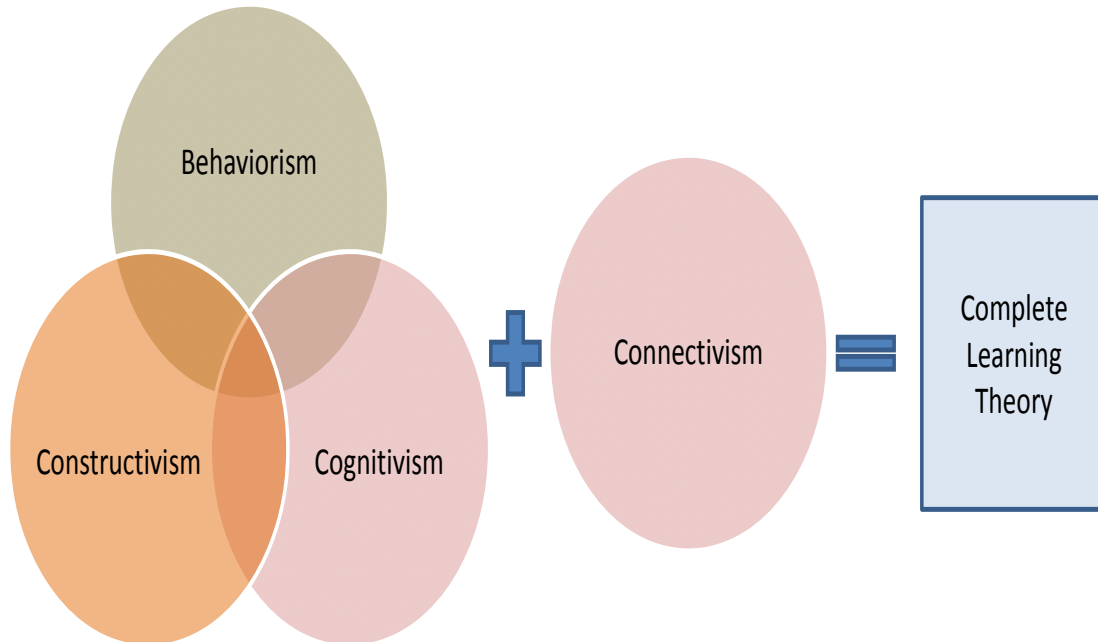


Figure 13. Complete learning theory (From Lepi, 2012).

Because these four building blocks of learning theory are related directly to the human aspect, it can be applied to any activity or domain, including systems engineering (Lepi, 2012). This thesis investigated the systems engineering activities during the systems engineering approach, identifying the types of learning that takes place during the different phases of a systems life cycle.

4. Quantifying Learning

Learning theories are subjective and unquantifiable, because of the many variables involved. Among the many variables are: the stakeholders' prior knowledge; rate of students' learning; clarity of teacher², duration of learning; environment and adaptability of project.

In this thesis, the proposed quantification of learning benefits was addressed in the context of quality and how it affects performance. The later

² Teacher here is defined as the provider of the knowledge or information to be imparted to the student.

chapters show this proposed relationship using the “general loss function” established by Choi and Langford (2009).

III. LEARNING ORGANIZATIONS AS SYSTEMS

Societies by themselves are complex, but they can be categorized into smaller groups; these groups comprised of two or more persons are known as an organization (Luhmann, 1995). Krugman also identified that the formation of each organization can be initiated functionally, geographically, behaviorally, and socially, often having a set of common goals that can be achieved either within the organization or between the organization and external systems (Krugman, 1996).

This chapter was scoped to look at an organization in any workplace through the lenses of learning and systems thinking. The organization in industry is required to keep pace with its surroundings (here defined as the environment, the competitors and the customers) in order to survive. One way to keep up this pace is through the introduction and maintenance of learning elements in the organization (Schwandt et al., 2000).

Senge and Peter (1990) argued that an organization that aims to evolve through learning and positive transformation is known as a “learning organization.”

Learning as defined Ambrose et al. (2010) as the change of knowledge, can take place in many forms, however in this project it will be referred to collectively as learning.

A. SYSTEM FORMATION AND ELEMENTS

Through the lens of systems thinking as defined by Weinberg (1975), an organization in industry can be seen as a system comprised of several core elements. Kept to scope for the purpose of system assessment in this thesis, these core elements within a learning organization are the following

- Employees
- Task Performed
- Goals

- Physical Infrastructure
- Competency

The interactions of these elements are shown in Figure 15. Each of these elements, although it can be broken down further, is intentionally kept at this level of abstraction to demonstrate the interactions and causality discussed in later sections.

As mentioned in the previous section, these elements are formed together functionally, behaviorally, or geographically. The forming of these elements can also be seen as formation within boundaries.

The learning organization, as a system interacts, with external systems. These systems include supporting organizations and sub-contractors, competitors and customers, as shown in Figure 14 (Schwandt and team, 2000).

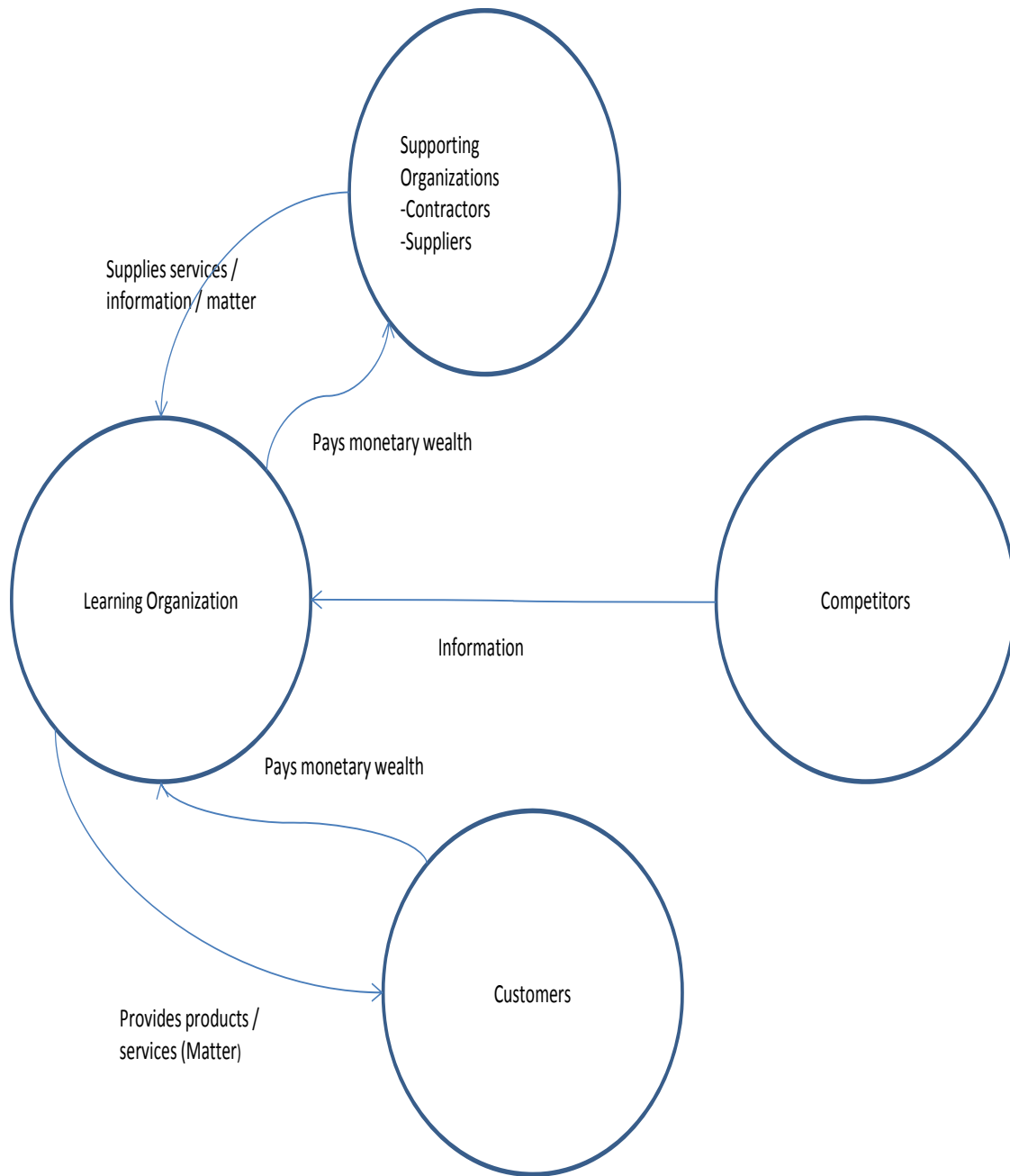


Figure 14. Interactions between the system with external systems.

Interaction with external systems forms some of the driving factors for learning organization as a system.

B. SYSTEM STABILITY

Assuming the resolution of each element is as depicted in the previous section (Chapter III, Section A), they, as individual elements, are stable for a period of time. A learning organization as a system, assuming that there are no interactions with external systems, is by itself stable.

As emphasized by Thompson (1917), an organization in the workplace needs to sustain itself and “grow” to survive; therefore we posit the assumption that the system of an organization has to be “unstable,” so that the organization is able to grow.

C. SYSTEM INTERACTIONS

Within a learning organization, elements in the system interact with each other, displaying causal relationship. These interactions cross boundaries in the form of Energy, Matter, Monetary Wealth, and Information (EMMI). Some of the major interactions are shown in Figure 15.

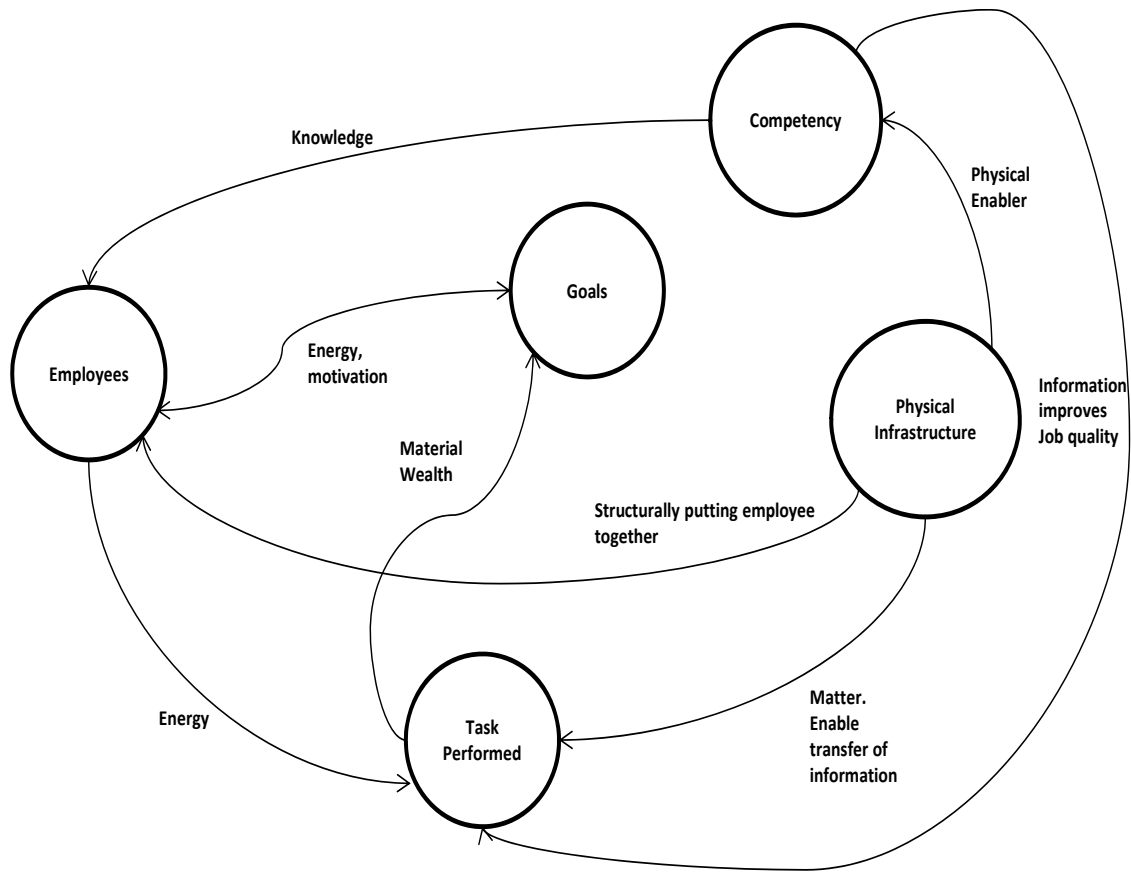


Figure 15. Interaction of EMMI within an organization.

D. EMERGENCE PROPERTIES

As elements in the learning organization interact with each other, the organization changes from one state as a result of the exchange of EMMI. The term 'state' as defined here, refers to the condition of element during the point of interest. This emerging organization can appear in the many forms

For example, when the employees have EMMI exchanges with physical infrastructure, both elements (employees and infrastructure) will experience a difference in state from its original and initial condition. In this case, the employees will occupy the physical space in the infrastructure.

E. ATTRIBUTES OF THE LEARNING ORGANIZATION AS A SYSTEM

Learning organizations like all organizations that are defined as a system, are driven by the motivation to maintain themselves or grow (Thompson, 1917); hence the attributes of an organization may be characterized as both relative and absolute. Table 2 shows some common attributes of an organization.

Table 2. Attributes of an organization.

Attributes	
Profit (\$)	Growth Rate
Headcount	Overhead
Number of offices	Market share (%)
Market share (quantity)	Employee Turnover Rate

Each of these attributes can be used similarly in a learning organization as the goals of a learning organization should be in sync with any organization. These attributes can otherwise be used as the Measurement of Performance (MOP) of the organization.

These attributes tend to indicate the performance of the organization based on its profit earnings, organizational size and reach. These MOPs of the organization, often expressed in terms of growth rate, overhead, market share percentage and turnover rate, help to show the progress of the organization with reference to itself or within its industry.

McMillian (2004) asserted in “Complexity, Organizations and Change” that by learning and adapting an organization can improve competency. These factors of learning and adapting play a critical part in an organization’s growth, hence contributing heavily to the MOPs of the organization.

Therefore, it is important to highlight that as learning elements improve work performance of the employees within the organization, there has an indirect relationship with the performance of the organization.

In the context of this thesis, the stakeholders³ identified with respect to a system, belong to some form of organization. As the competency level of an organization increases, the work performance of the employees will indirectly drive the organization's MOP to increase.

As the employee's competency improves, the organization's competency will improve. Resulting in improvement of the organization's MOP. This improvement in MOP will positively impact the organization's ability to manage and enhance system performances.



Figure 16. Relation between competency, organization MOP and system performance.

³ Stakeholders in this context are mapped and categorized into major groups to conveniently set direct association with the developmental and sustainment phase of the life cycle.

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IV. PROPOSAL FOR COLLABORATING SYSTEMS ENGINEERING AND LEARNING

A. PROPOSED COLLABORATIVE APPROACH

The purpose of this collaborative approach with learning theory and systems engineering is to allow stakeholders to see how aspects of learning interact with and within the systems engineering processes, and how these interactions impact decision making.

The different aspects of learning theories covered in previous sections will be introduced to existing systems engineering processes and activities, over the course of the general life cycle of a system. Stakeholders' means of learning from during the systems engineering activities will be examined and follow up actions shall be discussed.

To develop the collaborative approach, some parameters and assumptions have to be identified and established. The following sections help define and establish the basis of the proposed collaborative approach taken in this thesis.

B. KEY PARAMETERS

There are many driving parameters throughout a system's life cycle, some of which may occur only at specific phases of the life cycle, and some result from stakeholders' requirements. Examples of such parameters are organizational structure, laws, rules, and culture. However, as mentioned in Chapter I, the proposed integrated approach of applying elements of learning theory to the systems engineering approach focuses on three main parameters;

- Cost
- Schedule
- Performance

Every decision point during the process should impact one or more of the parameters identified above, regardless of the type of stakeholder involvement during the life cycle phase.

The life cycle of a system in the context of this thesis shall be scoped down to exclude several phases, such as disposal and prototype build. This is covered in the following chapter. The purpose of this reduced scope is to demonstrate the characteristics of learning within the systems engineering process.

C. STAKEHOLDERS

Types and variety of stakeholders can vary between projects and systems; however, we simplified and classified the types of stakeholders into six main groups, as shown in Table 3. These stakeholders are mapped and categorized to set direct association with the developmental and sustainment phase of a systems' life cycle.

Table 3. Stakeholder Classification.

Stakeholder	Responsibility
Customer/Sponsor (CM)	Provide funding for the project
Project Management Team (PMT)	Team in charge of cost management, resource management, schedule of the project.
Systems Engineering Team (SE)	Team in charge of all systems engineering activities for the system
Design Engineering Team (DE)	Team in charge of all technical design elements of the system
Contractor (CT)	Team in charge of development of system for the project.
Operator / User (OP)	Users of the system.

These acronyms shall be used in later sections and in Table 4. The responsibilities undertaken by the stakeholders in the above categories are generalized and based on interpretation from Pouloudi and Whitley (1997) and Donaldson and Preston (1995).

D. DECISION POINTS

Decision points are defined as the occurrence of a stakeholder making a decision that impacts the system's progress. These decisions point may be triggered by events, schedules, and information during the different phases in the life cycle.

E. ASSUMPTIONS

For the integrative approach to be undertaken there are several assumptions to be made regarding the system and its stakeholders. These assumptions are as follows:

- Stakeholders and decision makers shall be identified prior to the project definition. These stakeholders shall remain unchanged throughout the life cycle. There will be no new stakeholders arriving or leaving during the life cycle of the system.
- The system shall only take into account changes arising from iteration within the system and not from external sources, implying that changes and inputs from external systems and new stakeholders that drive and improve the system's performance, cost, and schedule will not be taken into consideration.
- Learning can take place anywhere in the life cycle and by all stakeholders regardless of stakeholder category, regardless of the systems engineering activity.
- All stakeholders have a constant learning ability and rate, implying that the learning rates of the stakeholders are consistent and constant throughout the course of the system's life cycle.
- Stakeholder experience is sufficient for the minimal development of the project at any phase of the life cycle or any systems engineering activity.

- All learning activities are assumed to have a positive impact on the key parameters, implying that change of knowledge attained from the learning elements cannot degrade the competency of the stakeholders.

V. QUALIFYING

A. AREAS OF INTERACTION

For the proposed approach mentioned in chapter IV, the different life cycle phases of a system in the systems engineering context, as shown in Figure 17, shall be used to interpret the current research on systems engineering methodologies and learning theories. Differing from the general life cycle process as shown in Figure 6, the life cycle phases seen in Figure 17 are conveniently identified to illustrate the phases where systems engineering activities can be related to learning activities. The result will be a mapping between the activities within the life cycle phases and types of learning that apply to those activities.

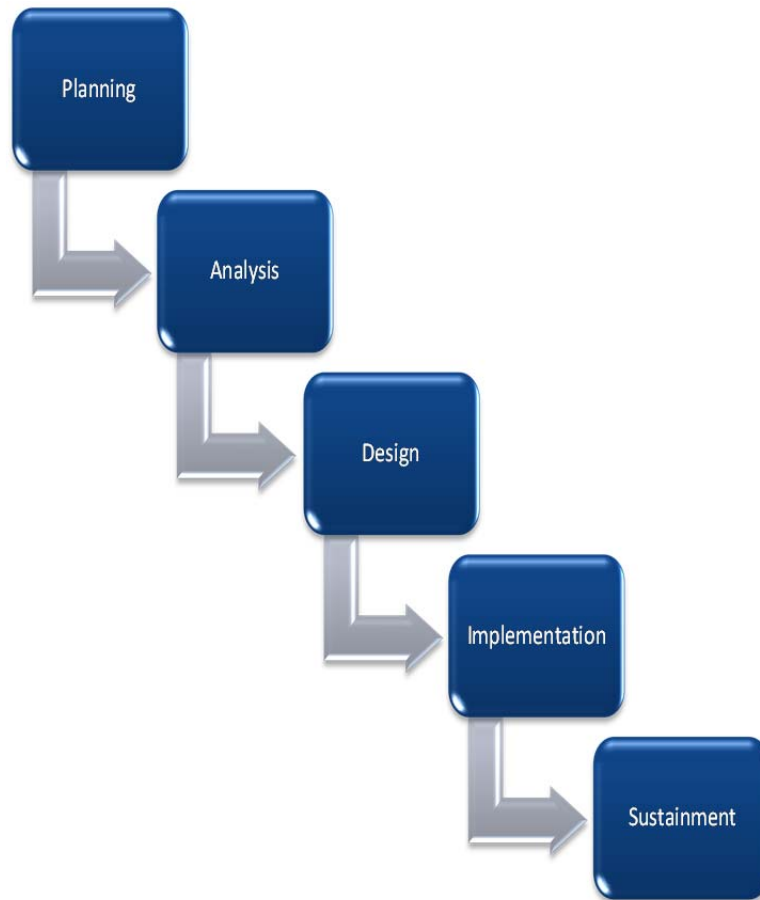


Figure 17. Life cycle process.

As learning activities can take place at any point and involve any decision maker throughout the identified phases of the above life cycle, the proposed approach can be applied accordingly.

1. Learning Types and Systems Engineering Activities Matrix

To initiate the collaborative approach, we first relate learning types and systems engineering activities. The stakeholders and their type of learning are also identified in the matrix. Shown in Table 4 is the matrix and association between,

- Key parameters of interest
- Stakeholders types
- Phase of life cycle
- Systems engineering activities
- Types of learning

It is important to highlight that the above mentioned activities are conveniently identified and categorized to illustrate the relationship of these activities for the purpose of this thesis. Definitions of types of learning can be found in Table 1.

Further, while the types of learning are generalized to behavior, cognitivism, constructivism, and connectivism, this set of learning types is by no means exclusive. The intent is to convey a means of differentiating these four types of learning as they apply to a select set of systems engineering activities within each of the life cycle phases carried out by systems engineers. The results of this mapping (and this thesis) serve to illustrate and distinguish between learning types and systems engineering activities. The implication of these results is that systems engineers need a broad range of education in types of learning to solve the problems associated with a typical systems engineering project. That education does not seem to be currently part of most academic curriculums, the Naval Postgraduate School being a notable exception with formal training and education for both instructors and students.

Table 4. Learning – systems engineering activity matrix.

Life Cycle Phase	System Engineering Activity	Key Parameters			Stakeholders Involvement						Types of Learning			
		Performance	Cost	Schedule	CM	SE	DE	CT	OP	PMT	Behaviour	Cognitivism	Constructivism	Connectivism
Planning	Project Definition	X	X	X	X	X			X	X	X	X		X
	Resource Definition		X	X						X	X	X	X	X
	Budget Anlaysis		X	X	X					X	X	X	X	X
	Constraints Analysis	X	X	X	X	X			X	X	X		X	X
Analysis	Stakeholders Analysis			X	X	X	X	X	X	X	X	X	X	
	Functional Anlaysis	X				X					X	X	X	
	Requirement Analysis	X	X	X	X	X					X	X	X	
	Operational Analysis	X				X			X		X	X	X	X
Design	Concept Design	X	X			X	X				X	X	X	X
	System integration	X	X	X		X	X	X			X	X	X	X
	Trade-off Analysis	X	X	X	X	X	X	X	X	X	X	X	X	X
	Prototype Development	X		X		X	X	X	X		X	X	X	
Implementation	Verification	X				X	X	X			X		X	X
	Validation	X				X	X	X			X		X	X
Sustainment	"ilibilities" Analysis	X	X	X		X			X		X	X		X
	Sustainability Analysis	X	X			X			X		X	X		X
	Upgradaebility Analysis	X	X			X			X	X	X	X		X

With reference to Table 4, the following section shows description of some of the key systems engineering activities and their types of learning. These systems engineering activities are intentionally highlighted to describe how different types of learning take place.

Project definition – All three key parameters are affected during the project definition phase; the main involved stakeholders are customers, project management team, systems engineers and operators. As this activity is task based, behavior learning will dominantly take place. Also, this activity being a definition process and has intensive information acquiring, there is also cognitive learning taking place. Lastly, the project definition phase requires a lot of information to be exchanged and transferred between stakeholders for objectives to be met, this form of learning is known as connectivism learning.

Operational analysis – This systems engineering activity pays attention to the operational aspect of the system, and impacts mainly on the performance parameter of the system. As the systems engineers will be gathering operational information from the operators, systems engineers and operators are the two main stakeholders in this activity. This activity by itself is a task based activity, hence involving the behavioral form of learning. The systems engineers will also create and evaluate the information being gathered from the operators on the types of operations, the form of learning represent cognitive learning. With this information, there is a need or systems engineers and operators to apply and construct operational scenarios and vignettes, this attributes to constructive learning. Lastly, there is a need for information and being passed between the systems engineers and operators, this results in connectivism form of learning taking place.

Trade-off analysis – During the systems engineering activity of tradeoff analysis, All the stakeholders are involved, the systems engineers, operators, design engineers and contractors will be concerned on performance parameter. The contractors, project management team, design engineers and customers are likely to be concerned about cost. The customers, project management team and the contractors are likely to be concerned on the schedule. Tradeoff analysis being a very task based, will have learning taking place in the behavior domain. There is also a need for systems engineers and project management team to create and evaluate the information being gathered from the different aspects of regarding the parameters, this form of learning represent cognitive learning. With this information, the stakeholders will then need to apply and tradeoff analysis or alternative solution, this form of learning

attributes to constructivism. Lastly, there is a need for information and being passed between the all the stakeholders, this results in connectivism form of learning taking place.

As mentioned, the three main intentions of this matrix are intended to accomplish the following:

- Collate and identify the different types of learning that are associated with the various systems engineering activities during the systems life cycle.
- Relate how key parameters are affected by different types of learning.
- Identify the key stakeholders' involvement with respect to the learning activities and systems engineering activities.

B. LEARNING TYPES DISCUSSION

1. Learning types

As mentioned, the definition of learning types can be found in Table 1. These types of learning can be said to have high correlation with the particular systems engineering activities.

Prior to this thesis, activities and transfer of knowledge in systems engineering have been taught in an informative and educational manner. However, the context of this thesis will take the viewpoint of:

- What is learned?
- How it is learned?
- Who learns it?

Prior to this thesis, there has not been much research conducted to characterize the type of learning within systems engineering approach. That being said, we can characterize and resolve the systems engineering activity by asking these questions.

- Can the activity be learned by understanding and remember? If so, there is behavioral learning involved.

- Can the activity be learned by following creating and evaluating? If so, there is cognitive learning involved.
- Can the activity be learned by analyzing and applying? If so, there is constructive learning involved.
- Can the activity be learned by recognizing and connecting? If so, there is connective learning involved.

This approach of using a question format helped decompose the systems engineering activities into learning domains and allowed for utilization of these categories.

For example, during the “design” phase of the life cycle and during the “concept design” system engineering activity phase; we can identify that behavioral, cognitive, constructive and connective types of learning can impact the decision makers (systems engineering and design engineering teams), so that the key parameters of cost and performance are improved.

2. Interaction between types of learning

Although each type of learning has its functional boundaries, there are still interactions between the different types of learning across the behavior boundaries that have a correlative effect on each other. Lepi (2012) in his article highlighted that because the platform (being the human) is common during complete learning defined by Lepi (2012) as previously highlighted in Chapter II, Each type and form of learning, although by themselves as individual discipline and field of study, can affect each other. This implies that, things being learned through one type of learning may affect the learning of another learning type; such transfer of knowledge can be both advantages and disadvantages depending on the type of knowledge on hand (Schwandt and team, 2000).

In the context of this thesis with respect the types of learning, there is loose coupling between the different types of learning. Having such loose coupling allows us to analyze and address each type of learning in insolation and independently.

Loose coupling as defined by Langford (2012) is as:

Loose coupling here implies that either many variables are at work and therefore observations how weak causality between actions of the two objects, or that observations do not reveal the linkage(s) between the two objects

At the same time with respect to the actual learned elements, it is desired that maximum cohesion of these elements because in the context of learning, optimal transfer of knowledge is preferred between the four different types learning mentioned.

Cohesion as defined by Langford (2012) is:

Cohesion is the characterization of the measure of binding between two objects through their interactions.

However, this statement is based on the assumption that the transferred knowledge is positively beneficial and compliments other types of learning during the same systems engineering activity.

3. Interaction of learning types between different systems engineering activities

With reference to Langford's definition of EMMI (2012), the interactions on learning types between systems engineering activities can be said to be crossing the functional and behavior boundaries. Similar to the previous section, this statement is established based on the human being the common platform.

Maximum cohesion is desired for learning elements between systems engineering activities as we want knowledge and information that is attained from the learning to be shared between activities, enabling positive emerging properties that may arise resulting from the interaction. This statement is made with reference to the assumption previously made that the transferred knowledge is positively beneficial and compliments other systems engineering activities.

4. Utilization

The information shown in Table 4 will allow the organization(s) and stakeholders to perform further analysis, and more importantly take action to

objectively develop the particular type of learning with respect to life cycle and the involved systems engineering activity. This section shows how this information can be positively used via the Kipling, (The Elephant's Child, 1902) problem solving method.

Kipling's (1902) 5W1H⁴ problem solving method is used here to initiate the utilization and implementation from the information attained. Kipling's 5W1H problem solving framework addresses a problem using "where," "what," "when," "who," "why" and "how," This method helps the problem solver to look at a problem from different aspects in a systematic fashion.

The information in Table 4 has-shown correlations of

- "Why" learning is important as it associated learning with the key parameters
- "How" learning take places via the four types of learning identified with the activities

The organizations and stakeholders can now extend the Kipling method for problem solving on the remaining 4Ws to introduce and improve learning in the organization. This is graphically represented in Figure 18.

⁴ Kiplings Methods to Problem Solving (Why, What, Who, When, Where, How.)



Figure 18. Kipling's 5W1H method applied to problem solving to be applied by organizations.

With information attained from Kipling's "what" domain, will be the identification of the type of contents required for the knowledge gain, hence allowing the organization to get knowledge resources required.

The organization can also use the "who" to identify who needs to learn the knowledge and who can teach the knowledge required.

The "when" domain will allow the organization to introduce the time element into the approach, this can help the organization to identify the best times to have learning activities with respect to intensity of the phase of the life cycle. Learning activities may include conducting lessons.

Lastly, the “where” domain will allow organization to identify the need for physical resources such as space or location. These resources are required for the learning activities to be executed.

The Kipling’s method acts as a general initiator to help the organization characterize the elements required for the enhancement of the “learning” aspect.

However, it is apt to emphasize that the Kipling method is used as an example and acts as an initiator, being only a small part of the process of successfully utilizing the input information (Table 4). The success and effectiveness of the implementation depends strongly on several other factors, such as plan execution, funding, and resource of manpower, which is not covered in this thesis due to time constraints.

5. Trade offs

With the deliberate effort by the organization to include learning related development into the system, resources will be needed for the execution of these learning enhancing activities. Resources can come from either existing pool or from external source, in monetary or manpower aspects.

Only when efforts to conduct analysis and development of the learning related activities are performed by external sources, will there be no lapse in projects schedule, and system performance as the manpower resources for the systems engineering activities remained unchanged. However, these additional resources may incur additional funding which may drive the cost of the overall up.

C. IMPACT ON DECISION POINTS AND STAKEHOLDERS

Having knowledge on learning attained from various phases of the life cycles and systems engineering activities, provides visibility into project dynamics and potential bottlenecks in progress (Appendix A) for the stakeholders. Better understanding of project thinking paradigms of learning may improve overall system performance. These learning activities can be further

resolved into decision points; in such there is visibility on how the types of learning activities affect key parameters at various decision points.

For example, knowledge attained by the systems engineer via the various forms of learning during the systems engineering activity of functional analysis can be “extracted” for use at another systems engineering activity at a later stage of the life cycle, e.g., verification. This knowledge attained via the various means of learning can be further developed and enhanced, allowing decisions to be made during the decision point on the systems engineering activity of verification.

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VI. QUANTIFYING

A. PROPOSED APPROACH

As mentioned in Chapter III, learning activities are subjected to many varying elements; hence it may not be feasible to quantify learning independent of other factors. However, the proposed approach aims to relate learning activities to performance of a system, via quality.

B. LEARNING AND PERFORMANCE

Based on the established assumption that all learning (identified in Table 4), creates only positive input back into the system life cycle. And in return only improves the key parameter. The relationship between learning and performance can be established via the element of quality.

When there is deliberate focus on enhancing learning in an organization, using the analysis and implementations proposed in the previous section; as a result of mastery, a positive change in knowledge will be manifested in the executed activities to be performed. It was estimated that \$156.2 billion spent on learning and development in 2011 in the US, approximating up to 56% of the organization's expenditure (American Society for Training & Development, 2012). This relation can be said to be known as the elements of mastery as shown in Figure 19 (Ambrose et al., 2010).



Figure 19. Elements of mastery (from Ambrose and Team 2010).

As mastery occurs and improve, indicating knowledge increase, there will also be an increase in the:

- Quality of the work delivered by the stakeholders
- Quality of decisions made from decision makers

When decisions and work of better quality are made and delivered during the systems engineering activities, the impact can be seen on the effects of the output, in terms of the performance parameters of the systems.

In other words, the more learning occurs, the higher the quality of the work and decision, therefore resulting in better performance of the system. This relationship can be seen in Figure 20.

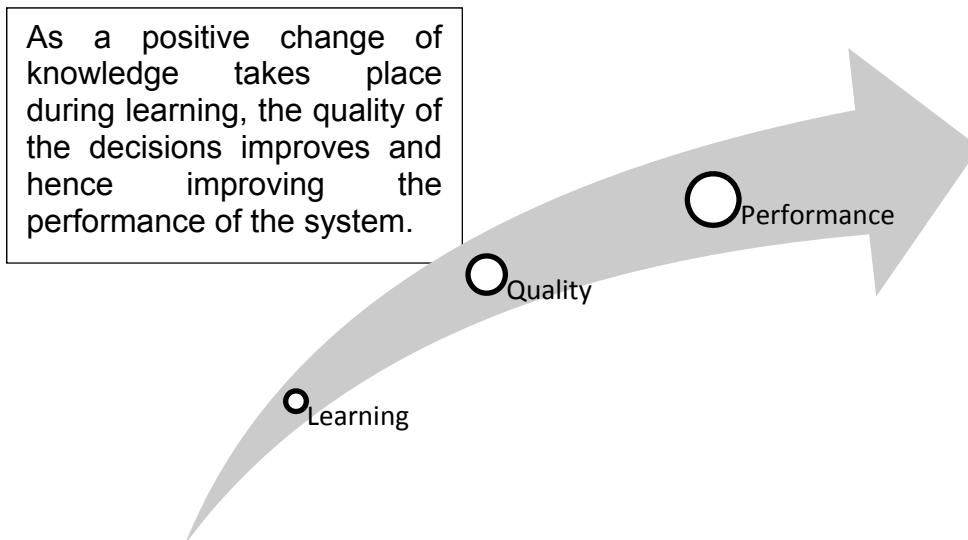


Figure 20. Relationship between learning, quality and performance.

1. Learning, Quality, and Loss Function

As mentioned in the previous section, learning is subjective, and learning can be associated with quality.

Conceptually, the relationship between quality and learning can be achieved by imposing a learning factor, l_f , into the generalized loss function equation, via the quality response function.

Recalling that learning is the change of knowledge, l_f can be defined as the learning factor resulting from the percentage of knowledge gained or lost after performing the learning activities when compared with the initial state. However, this percentage is based on the judgment of the personnel or organization performing the assessment.

For example, if the knowledge gained from after performing the learning tasked that is derived from and to be used in the systems engineering activity of requirement analysis is assessed by the organization as 20%. The learning factor l_f is 1.2.

Acknowledging that fact that quantifying the change of knowledge can be fairly subjective, we can incorporate some form of knowledge tests and assessment after the learning activity to measure the change in knowledge.

This measurement of performance attained from these assessments can perform as supporting justification.

2. General Loss Function and Performance

As mentioned in Chapter II, the proposed relationship between learning and performance can be linked via quality, using the generalized loss function. In such a manner, we can quantify the effects of learning by the loss of effectiveness in performing the systems engineering activities (Table 1). A convenient measure of effectiveness for a systems engineering project is the amount of rework required for satisfying the initial set of baseline requirements (Langford, 2013).

Mathematically, I_f can be multiplied to the quality response parameter in the calculating for the expected loss function, this is as shown in the below equation:

$$L_n(x) = -2 C_s (I_f * m)^n + C_s x^n (1 + (I_f * m)^{2n} x^{(-2n)}) \quad \text{Equation 2}$$

where:

L_n = expected loss function

C_s = proportionality constant

m = quality response

n = the shape parameter

I_f = learning factor

With the established relationship and based on the desired performance output from perspective of expected loss function, we are able to infer (as a gross estimation, then derive the required amount of learning element, from identifying the required learning factor, I_f .

This information can be utilized from the project organizational perspective as it allows for planning and justification of how much learning is required to

achieve the desired expected loss function, and in return the systems' performance goals.

With the knowledge of how much learning is required, the organization can now allocate resources to achieve the objective target of learning activities.

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VII. CONCLUSIONS AND THE WAY AHEAD

This chapter presents a summary of the research by repeating the original proposed way ahead

A. RESEARCH QUESTIONS

Each research question posed at the beginning of the research is repeated, followed by the answers with reference to where the questions are being answered in the thesis.

How effective are the existing methods of applying systems engineering to system life cycle problems?

In Chapter II, NASA and INCOSE have shown validation on the effectiveness of the application of systems engineering approach on the life cycles of several systems.

Which elements of learning theory apply in the life cycle of systems?

Table 4 of Chapter IV has summarized the relation between the main types of elements of learning theory, systems and systems engineering activities.

To what extent are elements of learning theories applied and used with systems engineering approach?

Chapter IV has shown how information attained from the relationship between elements of learning and systems engineering can be utilized to help improve the effectiveness of the system.

How will the system differ in terms of key performance parameters after elements of learning are introduced along with systems engineering approach?

Chapter VI as well as Table 4 of Chapter IV have summarized how key parameters can be affected and improved when the relationship between systems engineering and learning elements is established.

How will the stakeholders benefit from the incorporation of elements of learning theory in the systems engineering approach?

Chapter V has shown that when proposed activities derived from the relationship between learning elements and systems engineering are exercised, the stakeholders' work performance can be potentially improved.

How accurate are the existing methods of learning when applied to life cycle of the system?

Due to time constraints during the establishment of this thesis, the validation of application pertaining to this research question was proposed for future work. (see The Way Ahead, Chapter VII)

B. CONCLUSION

When looking at a system life cycle through the lens of systems engineering, it is seen that the elements of learning has direct impact on key parameters.

By identifying the types of learning taking place with respect to the systems engineering activities, we are able to put in perspective for the stakeholders the types of learning required.

When the association between learning and systems engineering, parameters is being established, we can characterize and utilized these information. This relationship takes place in the overlapped region as previously shown in Figure 1.

Characterizing of learning types and systems engineering activities allows the stakeholders to see the relationship between types of learning, types of knowledge required for the various systems engineering activity. This information can be used to organize and plan the required and content of activities so the knowledge can be positively enhanced. However, do note that this approach is based on several established assumptions mentioned in Chapter IV.

This thesis also put in perspective that learning has a relationship performance, via quality; highlighting that as knowledge increases, it will allow better work performed and decisions made. These changes having an impact of the quality will indirectly make an improvement in the performance of the system. This approach proposes that learning and knowledge change can be adapted via the general loss function; the better the learning factor, the lower the expected loss function of the system and hence the higher the system performance.

This information allows organization to justify and allocate the required resource from a technical and mathematical perspective, taking into account to factors such as return of investments.

C. THE WAY AHEAD

This thesis introduce a proposal and intended to show how learning and systems engineering can relate to each other, to show how justifications of the approaches are taken, and identify areas that are still lacking a form of concrete validation of the approach. Due to the time constraint faced during the development of this thesis, actual validations of process were not able to be performed. Hence, it is proposed that a validation be conducted to follow through the life cycle of a system through the lens of systems engineering, learning theories, and using the approach proposed in this thesis. This finding from this validation will allow the approach to be refined and reinforced, highlighting errors and flaws, if any.

As both systems engineering and learning theories are still progressive improvements, work may also be done to adapt and maintain this approach. New ways of learning, new methods of systems engineering, new categories of stakeholders, and new parameters may be introduced along the way. This addition, along with its maintenance, will improve and enhance the catalogue of information attained from this thesis.

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