

Development of an assessment tool to improve systems engineering performance in defense acquisition projects

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ABSTRACT

New product development is a generally difficult endeavour but particularly so in the defense sector because of the high stakes, unpredictability and accountability. The acquisition of defense systems is a complex process with numerous challenges and opportunities for improvement. There are major problems of cost overrun and schedule delays, and high failure rates in defense acquisition projects. Systems engineering plays a crucial role in the outcome of defense acquisition projects. Application of effective systems engineering introduces rigor and discipline to the development process and improves the outcome of projects. It is therefore imperative to improve the performance of systems engineering in defense acquisition projects. Additionally, the increasing complexity of warfighting capabilities necessitates more effective systems engineering in the program lifecycle. Therefore, the study aimed at developing an assessment tool to improve the performance of systems engineering during execution of weapon systems development projects.

The study was underpinned in the interpretivist research paradigm, and the data collection techniques used were case studies and document analysis. A case study research was conducted on three systems engineering projects of the Department of Defense. The case studies were analysed, and the results of the analysis were then used to design and develop an assessment tool. The assessment tool was developed based on the case study findings analysis. The developed assessment tool was evaluated using Subject Matter Expert reviews. The developed assessment tool and framework can be implemented during execution of weapon systems development projects.

This research study made both practical and theoretical contributions. Practically, it developed an assessment tool that can be implemented during execution of weapon systems projects to improve performance of systems engineering in weapon systems development projects. Theoretically, it contributed to the body of knowledge by identifying real-world challenges of systems engineering application in weapons systems development projects and proposing practical solutions. Future research should focus on improving the developed assessment tool to fit different weapon system types and organisations.

Key terms:

Systems engineering, defense acquisition, assessment tool, Department of Defense, systems engineering performance, weapon systems development

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LIST OF ABBREVIATION

AF:	Air Force
AoA:	Analysis of Alternatives
ASR:	Alternative Systems Review
CBA:	Capability-Basement Assessment
CDD:	Capability Development Document
CDR:	Critical Design Review
CM:	Configuration Management
CONOPS:	Concept of Operations
CPD:	Capability Production Document
DMMS:	Diminishing Manufacturing Sources and Materiel Shortages
DoD:	Department of Defense
DP:	Development Planning
DR:	Decision Review
EMD:	Engineering and Manufacturing Development
ESOH:	Environmental Safety and Operational Health
FCA:	Functional Configuration Audits
FD:	Full Deployment
FOC:	Full Operational Capability
FRP:	Full Rate Production
ICD:	Initial Capability Document
IMP:	Integrated Management Plan

IMS:	Integrated Master Schedule
IOC:	Initial Operational Capability
IOT&E:	Initial Operational Test and Evaluation
LCSP:	Life-Cycle Sustainment Plan
LRIP:	Low Rate Initial Production
MDA:	Milestone Decision Authority
MDD:	Materiel Development Decision
MSA:	Materiel Solution Analysis
N/A:	Not Applicable
O&S:	Operations and Support
PDR:	Preliminary Design Review
PM:	Program Manager
PRR:	Production Readiness Review
PSR:	Program Support Review
P&D:	Production and Development
QCA:	Qualitative Comparative Analysis
RDTE:	Research, Development, Test and Evaluation
RFP:	Request for Proposal
RTM	Requirements Traceability Matrix
RVA:	Requirements Validation Authority
SE:	Systems Engineering
SEP:	Systems Engineering Plan
SFR:	System Functional Review

SRR:	System Requirements Review
SSR:	Software Specification Review
SVR:	System Verification Review
TA:	Technical Assessment
TDM:	Technical Data Management
TMM:	Technical Measurement and Metrics
TMRR:	Technology Maturation and Risk Reduction
TPM:	Technical Performance Measures
TRA:	Technical Readiness Assessment
TRL:	Technology Readiness Level
US:	United States
WBS:	Work Breakdown Structure

1 INTRODUCTION

1.1 Background to the Research Study

Acquisition of major weapon systems is increasingly becoming challenging because of the growing uncertainty of the budgetary environment (Bogan, Percy, & Kellerman, 2017). The Department of Defense (DoD) acquires new product development through the defense acquisition system, which is an especially complex process with several improvement opportunities (Cilli M. V., 2015). The system is guided by centralised policies but permits decentralised and efficient implementation of acquisition activities which encourages flexibility and inspires innovation (Department of Defense, 2013).

New product development is a generally difficult undertaking irrespective of the field (Cilli M. V., 2015). In the defense sector, new product development is particularly difficult because it involves several government agencies and the environment is characterised by high stakes, uncertainty and accountability (Cilli, Parnell, Cloutier, & Zigh, 2016). According to (Markham & Lee, 2013), about 40% of new product developments fail to attain market success. These undertakings are faced with unwanted trends such as cost overruns and schedule creep (Cilli M. V., 2015). For example, between 1995 and 2014, 30 major defense acquisition programs were cancelled before they reached meaningful quantity production (Kendall, 2013). A highly effective defense acquisition system should therefore recognise ill-fated concepts before major resources are invested. In fact, as a matter of national security, the defense acquisition system must deliver more effective systems (Cilli M. V., 2015).

Systems engineering (SE) provides a foundation and creates a technical framework for delivery of capabilities to the defense forces (Department of Defense, 2013). Systems engineering is a multidisciplinary process for evolving and verifying life cycle balanced systems solution that meet customer needs (Lightsey, 2001). It is an all-inclusive integrative discipline encompassing different engineering disciplines such as structural, mechanical, electrical, software, and reliability engineering, to create a coherent system (Department of Defense, 2013). It supports the decision making process in project management by developing technical information and enhances development of systems that are resilient, reliable, certain and easy to modify (Department of Defense, 2013; Wittstruck, 2010). Systems engineering is applicable throughout the program life cycle, from concept development to disposal (Department of Defense, 2013)

Several studies have explored the relationship between systems engineering and program outcomes, and have attributed project success to application of effective systems engineering (Componation, Youngblood, Utley, & Farrington, 2008; Elm & Goldenson, 2012). (Kludze, 2003) showed that implementation of systems engineering reduces risk and improves technical performance. (Honour, 2013) also found a relationship between systems engineering and program compliance, complete success and technical quality. Other non-technical factors that influence how systems engineering is used have also been studied (Hodgson, Hubbard, & Siemieniuch, 2013; Honour, 2013; Bruff, 2008). According to (Mabelo & Sunjka, 2017), systems engineering enables projects to be more controllable and efficient.

(NASA, 2007) noted that systems engineering should focus efforts on assessments to optimise the whole systems design and not compromise one system over the other. Measurement of performance over the life cycle of a system is critical to the DoD (Brady, 2015). Therefore, it is necessary to assess and improve performance of systems engineering during weapon system development.

1.2 Motivation of the Study

Systems engineering involves application of critical thinking to capability acquisition (Department of Defense, 2013), and plays a pivotal role in the success of a program. Applying systems engineering in defense acquisition has shown to improve the outcomes of programs. For example, (Government Accountability Office, 2016) found that programs that conducted a detailed systems engineering overall had good outcomes, whereas programs that had little systems engineering had poor outcomes.

Because of the role it plays in improving program performance, the DoD revised the defense acquisition system to incorporate emphasis on systems engineering. Despite the efforts, many challenges still remain with regards to performance of systems engineering in defense acquisition. According to (Brady, 2015), defense force capabilities are increasingly becoming more complex and this necessitates more effective systems engineering in the life cycle. The DoD depends on data to make decisions which impact the defense force capability, and during decision making, program performance is prioritised over cost and schedule ((Brady, 2015; Cilli, Parnell, Cloutier, & Zigh, 2016).

It is therefore imperative to improve performance of SE in defense acquisition to yield better program outcomes. This study will contribute to the industry by developing an assessment tool to improve systems engineering performance in defense acquisition projects. Furthermore,

most work that has been done relates to assessment of SE performance after completion of the project and not during execution. Therefore, this study aims fill this gap by developing an assessment tool that can be applied during the execution of weapons systems development where decisions can be made to overcome obstacles.

1.3 Research Problem

The engineering challenge of the DoD is to obtain beyond-cutting-edge weapon systems within budget and schedule (Brady, 2015). Although the DoD continues to develop and deliver extremely effective systems to the defense forces, these weapon systems are increasingly becoming more complex (Brady, 2015).

Weapon systems development projects can be challenging and often lead to high cost overruns and severe delays. Weapon systems are usually very complex and interdisciplinary, and they can lead to catastrophic failures at any stage during their system lifecycle. Complex controls formulated for high technology projects are often an excessive, which stifles initiative and escalates cost with limited reward. Additionally, development projects often end in failure through lack of correctly applied systems engineering processes. (Government Accountability Office, 2016) supported this premise by stating that although the acquisition problems were believed to be due to unexpected changes in requirements, they were more directly linked to a lack of systems engineering. These failures indicate that a lot of funds are spent on development projects before termination. The opportunity cost related to this is that the funding could otherwise be used to develop and possibly increase the delivery of superior capabilities to the defense forces (Cilli M. V., 2015). In addition, failed programs present challenges with securing defense forces capabilities (Bogan, Percy, & Kellerman, 2017).

When effectively implemented, systems engineering introduces discipline and rigor to the process and reduces risk (Government Accountability Office, 2016), thus highlighting the significance of SE. Therefore, it is crucial to improve performance of SE in defense acquisition programs. Despite the varied causes of system engineering failures being addressed from many defense acquisition projects, the proposed solution is to develop an assessment tool that can be used in the defense industry to improve the systems engineering practices which can contribute to solving the cost overruns and delays in defense acquisition projects.

1.4 Research Aim and Objectives

The aim of the study is **to develop an assessment tool to assess the systems engineering activities during execution of any weapon systems development project.**

The research aim was achieved through the following specific objectives:

1. To develop and implement a framework to assess performance of several weapon system projects.
2. To conduct a detailed systematic review analysis on systems engineering in defense acquisition.
3. To determine failures and success in weapon system development projects.
4. To develop an assessment tool (questionnaire) designed to improve performance of systems engineering in weapon system development projects.

1.5 Research Questions

The research questions of the study are:

1. Are systems engineering activities adequately implemented in defense acquisition projects?
2. What are the challenges that face defense acquisition projects?
3. Why do most of the defense acquisition projects fail to meet the cost and time constraints?
4. How can systems engineering performance be improved during the execution of defense acquisition projects?

1.6 Contribution of the Research

The current performance assessment tools in existence are applied after a project has been completed. There is a gap with regards to performance assessment tools used during execution of defense acquisition projects. The study will contribute to the industry by developing an assessment tool to improve systems engineering performance during execution of defense acquisition projects. The study will provide a solution that can be used as an industry standard assessment tool. The study will also contribute to the body of knowledge of the field.

1.7 Research Design

The study applied a qualitative research methodology in the investigation to establish an assessment tool designed to improve systems engineering performance during the execution of defense acquisition projects. The qualitative method was used because it is more suitable for this study as it permits exploration of complex situations and theories (Stake, Qualitative case studies, 2005).

The study adopted the case study methodology and specifically, cross-case analysis. The target case studies were defense acquisition projects (for weapon systems) of the DoD, which are typically interdisciplinary, complex and large. The selected case studies were studied and analysed against one another. Using the knowledge obtained from analysing the case studies, an assessment tool was developed. The developed assessment tool was verified by subject matter experts who have decent experience within defense development projects.

The case study research method was used to obtain insightful qualitative interpretation for developing and implementing an assessment tool that can assess the performance of the project. The case study sources of evidence were obtained from open literature and archival records.

1.8 Limitations of the Study

The context of the study is developing an assessment tool to improve the systems engineering performance in the execution of developing **weapon system** projects.

The study focuses on the developmental phases of the defense acquisition lifecycle only. The production and deployment, and operations and support phases are excluded in this research.

1.9 Structure of the thesis

Chapter One: Introduction. Introduces the research topic of the study. The chapter describes the research problem, motivation and contribution of the study. It highlights the aim, objectives and research questions of the study. It also describes the research design and limitations of the study.

Chapter two: Literature review. Details a systematic review of literature. The chapter discusses the systems engineering framework and the defense acquisition life cycle. It further discusses the application of systems engineering in defense acquisition, the challenges of defense acquisition programs and the root causes of failure in defense acquisition. The chapter then concludes by examining previous efforts to improve systems engineering performance in defense acquisition.

Chapter three: Research Methodology. Outlines the research paradigm and underpinning of the study. The chapter presents the research approach, methodology and data collection techniques of the study.

Chapter four: Case Study Description. Provides a description of the case studies used in this study.

Chapter five: Development of the Assessment Tool. Interprets the findings and analysis from the case study, which led to the development of the assessment tool. The chapter outlines the purpose of the assessment tool, the development process, the focus and content of the assessment tool.

Chapter six: Evaluation of the Assessment Tool. Presents the evaluation method used in the study to evaluate the assessment tool. The results and findings of the evaluation are presented in this chapter.

Chapter seven: Conclusion Presents the conclusion and recommendations of the study.

1.10 Summary

Chapter one provided a background to the study topic and motivation for the study. It described the research problem and highlighted the aim, objectives and research questions of the study. The chapter described the contribution of the research to the industry. It thereafter described the research design, limitations of the study and concluded by outlining the structure of the thesis.

2 LITERATURE REVIEW

2.1 Introduction

Systems engineering is applicable in various industries such as aerospace, defense, telecommunication, healthcare and automotive manufacturing. It is beneficial because it contributes to performance and outcome of programs. Defense acquisition programs particularly are faced with the major challenges of cost growth, schedule delay and performance problems (Government Accountability Office, 2016). These challenges have been directly associated with lack of effective systems engineering (Government Accountability Office, 2016). Effectively implementing systems engineering principles ensures mitigation of cost and schedule risk in program phases and increases program success (Government Accountability Office, 2016). Therefore, it is crucial to investigate how systems engineering can be applied in defense acquisition and how it can be used to improve performance of defense acquisition projects. This literature review provides a detailed assessment of systems engineering in the context of defense acquisition. It describes the systems engineering framework and defense acquisition life cycle in detail.

The chapter examines the application of systems engineering in defense acquisition and the challenges facing defense acquisition projects. The root causes of failure of defense acquisition projects are also explored. The chapter concludes by reviewing previous efforts to improve systems engineering performance in defense acquisition projects.

2.2 Systems Engineering

Systems engineering is defined as an interdisciplinary approach that involves technical efforts to realize a balanced set of systems solutions and satisfy customer needs (Holmgren, 1993). It is a disciplined methodical approach to problem solving for design, management, operations and retirement of a system (Defense Acquisition University, 2003). The concept was first used in the late 1950s with the introduction of the Intercontinental Missile Program (Holmgren, 1993), and was formed from the need to balance engineering specialties together in an end product (Holmgren, 1993). Systems engineering enables integration of multidisciplinary efforts to meet program goals with respect to cost, schedule and performance using an optimum design solution (Holmgren, 1993). It ensures that various engineering disciplines are properly

coordinated and utilized so that defense systems are delivered in an effective, timely and affordable manner (Defense Acquisition University, 2003). It is comprehensive because it considers both engineering and non-engineering areas (Holmgren, 1993).

Preparation of a systems engineering plan as a management tool guides the SE activities of a program during its lifecycle (Government Accountability Office, 2016). Some functions of systems engineering include: develop user training equipment and procedures, create and sustain system configuration management, develop breakdown structures of work, and offer information for management decisions (Holmgren, 1993). As a system becomes bigger and more complex, the design, development and production necessitate the integration of various activities and processes (Department of Defense, 2013).

The benefits of systems engineering include, but are not limited to: aiding development of realistic and attainable goals of a program; providing an integrated perspective of technical efforts across the system lifecycle; emphasizing the application of consistent, integrated and replicable processes to reduce risk; and providing insight into resource requirements (Department of Defense, 2013). Studies have shown that implementation of systems engineering increases the success of a program. It is therefore imperative to incorporate suitably tailored systems engineering principles during the execution of a program or project.

2.2.1 Systems Engineering Processes

The application of Systems engineering (SE) varies depending on the project, team and organization. There are several systems engineering frameworks, such as the Research, Development, Test and Evaluation (RDTE) life cycle, System Acquisition or Production life cycle, Planning and Marketing life cycle, and Concurrent Engineering life cycle model (Sage & Rouse, 2009). The system engineering framework discussed in this chapter is the framework used in the Department of Defense (DoD).

The DoD Systems Engineering Process is a comprehensive problem-solving process applied successively top-down by integrated teams (Lightsey, 2001). The process translates program requirements into a system of product and process descriptions for decision making (Lightsey, 2001). Systems Engineering Processes provide a framework for planning, managing and implementing technical activities in the acquisition life cycle for effective delivery of a capability (Department of Defense, 2013). They should be applied from concept definition and also constantly throughout the system life cycle (Department of Defense, 2013).

The DoD system engineering framework comprises a total of 16 processes, eight technical processes and eight technical management processes (Figure 1). These processes provide

an approach to increase technical maturity of a system and ensure that there is a balance between performance and schedule, cost, risk and design limitations of a capability being developed (Department of Defense, 2013).

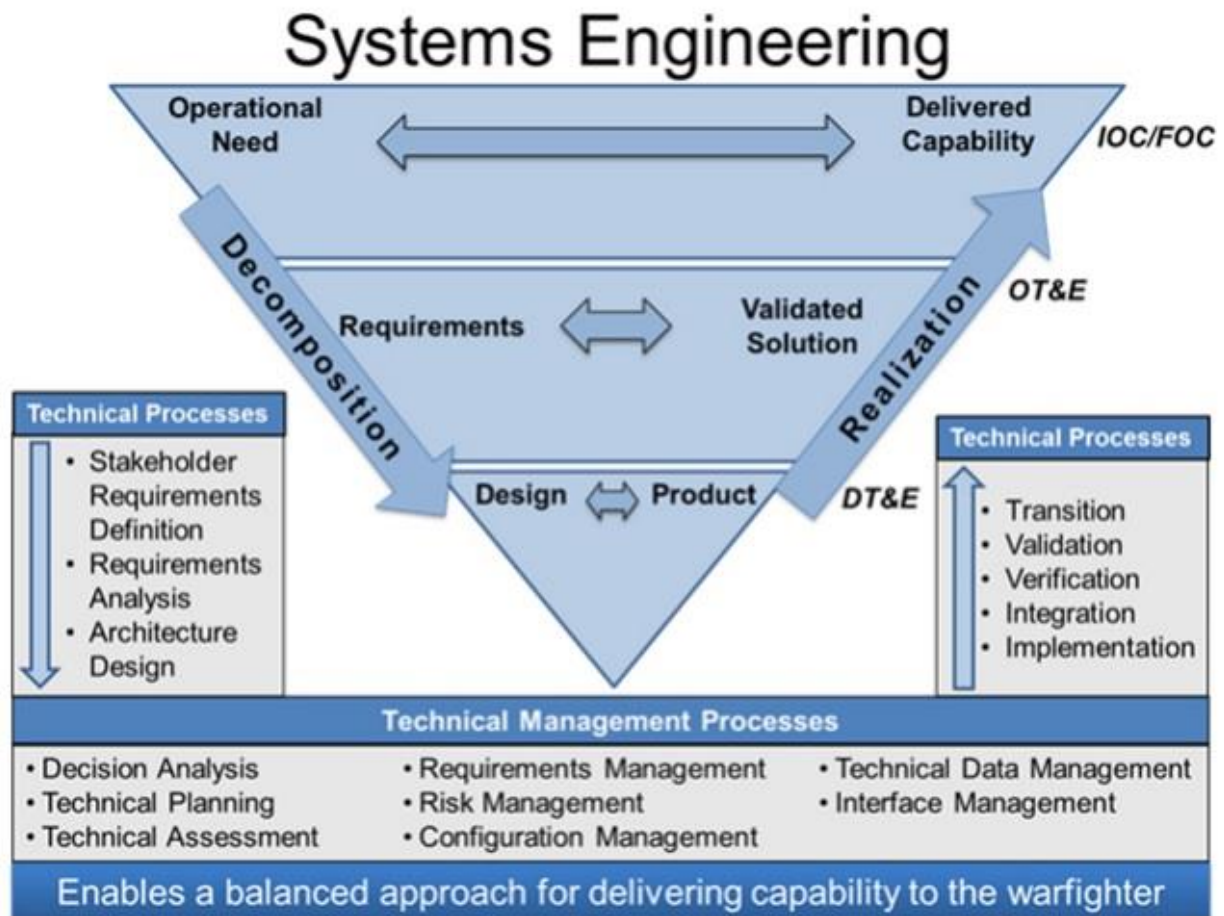


Figure 1: Systems engineering processes. (Department of Defense, 2013)

The eight technical processes are closely correlated with the phases of the acquisition lifecycle and involve the top-down design processes and bottom-up realization processes that transform user needs into operational capabilities (Department of Defense, 2013). The technical management processes support the program manager and systems engineer to meet program goals while the technical processes assist the SE team to make sure that the operational requirements of the stakeholders are accurately reflected by the delivered capability (Department of Defense, 2013). As a program progresses into advanced phases of the acquisition lifecycle, the level of systems engineering needed to support these processes decreases (Department of Defense, 2013). The following section discusses the individual SE processes in detail.

2.2.1.1 Technical Management Processes

In DoD systems engineering, the eight technical management processes provide a structured approach for obtaining and managing technical information and tasks crucial for success of a program (Department of Defense, 2013). These processes are constantly applied through the lifecycle of the system and form the basis for managing the system development (Department of Defense, 2013). The technical management processes are discussed in detail in the following section.

2.2.1.1.1 Technical Planning Process

The Technical Planning Process involves defining the technical effort needed for developing and sustaining a system (Department of Defense, 2013). The process provides measurable inputs for program planning and cost estimations of the life cycle (Department of Defense, 2013). It yields a framework for completing technical activities that decrease risks and increase maturity of the product (Department of Defense, 2013). Technical planning considers the resources required for developing the system, and encompasses the strategy for technical audits and reviews of the program (Department of Defense, 2013). The technical plan of a program should be comprehensive and clear, context of the organization should be reflected, and the plan should observe all pertinent policies (Department of Defense, 2013).

Activities involved in technical planning include: defining goals and scope of technical effort; detecting limitations and risks; establishing duties and tasks; creating schedules and costs; and finding possible tailoring areas for Milestone Decision Authority approval (Department of Defense, 2013). Three main documents established in technical planning are: Work Breakdown Structure (WBS), Integrated Master Plan (IMP), and Integrated Master Schedule (IMS) (Department of Defense, 2013). These documents define and record tasks necessary for system development and delivery (Department of Defense, 2013). It is the responsibility of the systems engineer and program manager to ensure that technical planning stays up to date throughout the acquisition lifecycle (Department of Defense, 2013). They should also monitor the IMS to ensure realistic activity durations and resources (Department of Defense, 2013).

2.2.1.1.2 Decision Analysis Process

Decision Analysis translates a general decision opportunity into a justifiable, traceable and executable plan (Department of Defense, 2013). It involves assessing alternatives and choosing the optimum decision, and offers a basis for selecting a feasible and operative alternative from the many options (Department of Defense, 2013). Decision analysis concerns

technical decisions made at all levels from top to bottom. It comprises separate analyses at lower-levels and combines them into upper-level view important to the decision makers (Department of Defense, 2013). It is fundamental in planning, managing and implementing an operative and efficient program at any point in the lifecycle (Department of Defense, 2013).

The decision analysis process involves the following steps: reviewing requirements and presumptions; structuring decisions; identifying tools and procedures for analyses; establishing decision criteria; evaluating alternatives against criteria; synthesizing results; developing decision briefing; and making suitable recommendations (Department of Defense, 2013). A well-executed decision analysis enables the program team to identify the impact of different uncertainties, find appropriate courses of action, and accurately communicate outcomes to the decision makers (Department of Defense, 2013). It results in sound recommendations and plans of action (Department of Defense, 2013).

2.2.1.1.3 Technical Assessment Process

This process determines technical progress and evaluates the requirements and plans of the program. It allows for comparison of realized outcomes with defined criteria to gain understanding of the present level of technical knowledge, status, maturity of the program and risk (Department of Defense, 2013). Technical assessment (TA) activities should start in the early stages of the life cycle (Department of Defense, 2013). Activities carried out in this process include: developing event-based technical planning; identifying suitable metrics and measures; establishing measures of performance to evaluate program progress; analysing risk and develop strategies of mitigation; and assessing technical maturity of the program (Department of Defense, 2013).

The measures and metrics used in TA include: Technical Performance Measures (TPM), Technical Measurement and Metrics (TMM), and the Program Support Review (PSR) (Department of Defense, 2013). The TMM provide understanding of issues that have actual impact on performance, cost, schedule and risk (Department of Defense, 2013). The TPM compare planned and actual technical design and development, and documents the progress of the program (Department of Defense, 2013). The SPR detects and resolves planning and implementation issues early before review of an acquisition milestone (Department of Defense, 2013). Technical assessments are closely linked to technical planning and decision analysis (Department of Defense, 2013).

2.2.1.1.4 Requirements Management Process

Requirement Management ensures delivery of a capability that satisfies the intended performance stipulated by the end user (Department of Defense, 2013). The needs of the end user are generally identified during the stakeholder requirements and definition and the requirements definition processes. Requirements management involves understating the impacts of proposed requirement changes to any system element, and updating documentation with justification for the accepted changes (Department of Defense, 2013). It applies traceability of requirements in a bi-directional manner, which results in effective system requirements management (Department of Defense, 2013).

Execution of an effective requirements management in conjunction with the configuration management process enables the program to avoid or alleviate unpremeditated effects of the changes, which supports the basis for system affordability (Department of Defense, 2013). A Requirements Traceability Matrix (RTM) records all system requirements, their decomposition, and justification for all entries and their changes (Department of Defense, 2013). It is important that all relevant stakeholders completely understand the impacts of the changes proposed to requirements before approving their incorporation into the system design (Department of Defense, 2013).

2.2.1.1.5 Risk Management Process

Risk management is an all-encompassing process that involves identifying, analysing, mitigating and tracking program risks (Department of Defense, 2013). It is the main mechanism for mitigation of program uncertainties and thus is essential in attaining program schedule, cost and performance objectives (Department of Defense, 2013). Effective management of risks improves technical performance of a system and establish achievable schedule estimates and life cycle costs (Department of Defense, 2013). Both programmatic and technical risks should be managed at every phase of the life cycle (Department of Defense, 2013). Risk management is most efficient when incorporated with the systems engineering and management processes of the program (Department of Defense, 2013).

A risk is an undesirable occurrence that might or might not happen in the future (Department of Defense, 2013). The three components of a risk are: a future root cause (yet to occur); probability (chance or likelihood); and consequence (effect or impact) (Department of Defense, 2013). Plans for risk mitigation should put more emphasis on causal factors of the risk than management of outcome because completely removing the risk root cause prevents its consequence (Department of Defense, 2013). Risk management also includes the situation

when efforts of mitigation fail and the risk materializes (Department of Defense, 2013). The key activities in Risk management are: risk identification, risk analysis, risk mitigation planning, risk mitigation plan implementation, and risk tracking. Identifying of risk early is fundamental to the success of the program (Department of Defense, 2013).

2.2.1.1.6 Configuration Management Process

Configuration management (CM) provides technical insight into the system design at all levels (Department of Defense, 2013). It supports the program to identify and manage changes to the technical baseline and ensures that the cost, performance and schedule impacts of the changes and the related risks are assessed (Department of Defense, 2013). The baselines critical to implementation of CM are functional baseline, allocated baseline, and product baseline (Department of Defense, 2013). An effective CM establishes and maintains these baselines, which facilitate successful capability production and delivery (Department of Defense, 2013).

Configuration management activities enable traceability of designs to system requirements, evaluation and incorporation of change requests, and consistency of a product with design requirements and system elements (Department of Defense, 2013). The primary functions of configuration management include: configuration management and planning, configuration identification, configuration change management, configuration status accounting, and configuration verification and audit (Department of Defense, 2013). These functions make up the configuration management standard and ensure that consistency in the program is maintained between the product and its configuration information throughout the life cycle (Department of Defense, 2013).

2.2.1.1.7 Technical Data Management Process

Technical data is any data except computer software that is scientific or technical in nature (Department of Defense, 2013). The Technical Data Management (TDM) process enables the program to identify, obtain, manage, retain, and ensure access to technical data needed to support the system (Department of Defense, 2013). The TDM concerns include protection and understanding of intellectual property, maximization of product support options, attainment of competition goals, and facilitation of performance of downstream functions of the life cycle (Department of Defense, 2013). Activities associated with TDM include: identification of data requirements; acquisition of data; receipt, verification and approval of data; storage, maintenance and control of data; application and exchange of data. (Department of Defense, 2013).

Protection of the system data is executed by the program manager (PM), whether it is managed and stored by the Government or contractors (Department of Defense, 2013). Protection of data concerning information subject to restrictions is done according to the applicable contract, guidance or agreement (Department of Defense, 2013). Distribution declarations should be included in all the data deliverables. It is important to establish processes to protect data with critical technology information, and also ensure that intellectual property, proprietary, limited distribution data are appropriately handled, whether they are in digital format or hard copy (Department of Defense, 2013).

2.2.1.1.8 Interface Management Process

The Interface Management Process establishes a framework defining, managing and ensuring compliance of system interface among its elements, and also with other systems (Department of Defense, 2013). The process ensures that internal and external interface requirements and changes are well documented according to the Configuration management plan of the program (Department of Defense, 2013). Interfaces contribute an important role in systems and systems of systems that interrelate to deliver a combined capability (Department of Defense, 2013). Complex systems comprise many different types of interfaces (Department of Defense, 2013). Besides technical SE aspects and integration, interface management should also consider programmatic concerns such as responsibilities, scheduling and funding (Department of Defense, 2013).

The duties of the systems engineer in interface management include: defining and developing interface specifications; evaluating interface compliance; monitoring interface integrity and viability; and developing interface management plan (Department of Defense, 2013). The PM should form an Interface Control Working Group (ICWG) consisting of suitable technical representatives, which serves to establish interface requirements, focuses on interface in detail and resolves issues timely (Department of Defense, 2013).

2.2.1.2 Technical Processes

Systems engineering technical processes are the life cycle processes. The processes coexist and the significance of a particular process is dependent on the phase and maturity of the system design. They ensure that the design of the system and the capability delivered reflect stakeholder requirements (Department of Defense, 2013). The technical processes are presented below.

2.2.1.2.1 Stakeholder Requirements Definition Process

During this process, the operational inputs of the significant stakeholders are transformed into top-level technical requirements (Department of Defense, 2013). The program manager and systems engineer collaborate with the user to establish and define operational requirements, performance parameters and limitations, and to make sure that design and requirements considerations are addressed. The goal of this process is to transform customer needs into program and system requirements which include performance objectives, and affordability, schedule and technical constraints. The major activities involved in this process are to; elicit objectives of stakeholder capability, define stakeholder requirements, and analyse and maintain stakeholder requirements (Department of Defense, 2013).

Implementation of stringent systems application is vital because most requirements will be defined through system decomposition (Department of Defense, 2013). Failure to implement a comprehensive Stakeholders Requirements Definition process can lead to misinterpretation of customer needs, requirements creep, unforeseen modifications, cost growth and schedule slip (Department of Defense, 2013). The documents created for stakeholder requirements include Initial Capabilities Document (ICD), Capability Development Document (CDD), and Capability Production Document (CPD).

2.2.1.2.2 Requirement Analysis Process

In Requirements Analysis, the stakeholder requirements identified during stakeholder requirements definition process are decomposed and detailed to create a total system of functional and performance requirements (Department of Defense, 2013). The requirements are disintegrated into logical, attainable, measurable, and verifiable top-level requirements (Department of Defense, 2013). The requirements developed should include technical, functional and performance constraints, life cycle and development cycle time (Department of Defense, 2013). Requirements analysis provides both a mechanism for supporting trade-off analyses and a framework for accurately evaluating performance of the system (Department of Defense, 2013).

The procedure of defining requirements involves: analysing needs of the user, translating user requirements into basic functions, developing measurable performance requirements, defining the functions the system is required to accomplish, defining implementation constraints, and translating performance requirements into defined technical functions (Department of Defense, 2013). Inadequately crafted requirements can result to serious cost, schedule and performance challenges thus increase program risk (Department of Defense, 2013). Well-

crafted requirements on the other hand, enable stakeholders to evaluate system performance during the later stages of verification and validation (Department of Defense, 2013).

2.2.1.2.3 Architecture Design Process

This is a synthesis process that translates the outputs of stakeholder requirements definition and requirements analysis into alternative design solutions and establishes a final design solution (Department of Defense, 2013). The alternative design may comprise software, hardware and human elements, and their enabling processes (Department of Defense, 2013). The architecture design process, together with the previous processes ensure early awareness of technical risk and enables early establishment of mitigation strategies (Department of Defense, 2013). It produces several possible solutions, evaluates them, and describes the execution of system individual components (Department of Defense, 2013).

The functional architecture defines the system architecture by assigning functions to hardware or software, facilities, database, and human operations (Department of Defense, 2013). The physical architecture comprises product structures of the physical solution (Department of Defense, 2013). The systems engineer should consider mature technologies to meet user needs, and the system architecture should follow rigorous systems engineering and meet applicable industry standards. Upon identification, the system architecture is placed under Configuration Management and is complete when the system has been disintegrated to the lowest system element (Department of Defense, 2013).

2.2.1.2.4 Implementation Process

The implementation process produces an elaborate design down to the system elements at the lowest level in the hierarchy system. Depending on technology maturity, the process can create, buy or reuse system elements (Department of Defense, 2013). Implementation increases maturity, decreases risk, and ensures that the system is ready for integration, verification and validation (Department of Defense, 2013). The process also involves developing supporting documents of the system elements, for example operation manuals (Department of Defense, 2013). The implementation process encompasses two efforts, design and realization.

Implementation starts in the Materiel Solution Analysis phase of the acquisition life cycle, where it is decided whether to develop, buy or reuse the preferred materiel solution (Department of Defense, 2013). The analysis includes efforts such as simulation and modelling, experiments and prototypes, which can be used to assess competing systems (Department of Defense, 2013).

Realization. Is the process of constructing system elements with the use of defined materials and production procedures identified during design. Planning for production early enhances success in realization and delivery of the required capability (Department of Defense, 2013).

2.2.1.2.5 Integration Process

The integration process thoroughly incorporates low-level system elements into top-level elements with verification up to when the system itself materializes (Department of Defense, 2013). It assists to increase system maturity, decrease risk, and prepare transition of the system to the defense forces (Department of Defense, 2013). Development of an integration plan increases the success of a program. The plan describes the integration stages in which elements are sequentially integrated to create upper-level elements, and ultimately the finished product (Department of Defense, 2013). Sequential integration phases comply with the sequence of the program integration plan (Department of Defense, 2013).

For a successful integration process, an interface management process is essential (Department of Defense, 2013). Interface control should be implemented early under stringent configuration control (Department of Defense, 2013). All external interfaces of the program should be documented in the program's Systems Engineering Plan (SEP) (Department of Defense, 2013). Integration actions verify that accurate and effective interface specifications are documented (Department of Defense, 2013). Integration phases follow the integration plan of the program and deliver the final product ready for verification and validation (Department of Defense, 2013).

2.2.1.2.6 Verification Process

Verification provides confirmation that the system element meets the specifications as defined in the performance, functional and allocated baselines. It reduces risk in implementation of a system and ensures that the program detects deficiencies in system elements before incorporation at the next level (Department of Defense, 2013). The verification process starts during Requirements Analysis. The process determines the procedure (how and when) of verification of requirements, the activities, and resources required for verification (Department of Defense, 2013). The methods used to achieve verification include demonstration, examination, analysis and test (Department of Defense, 2013).

The program verification activities are recorded in the Functional Configuration Audits (FCA) and the System Verification Review (SVR) (Department of Defense, 2013). Verification of system designs is conducted at all level of the physical architecture using the combination of methods that is cost-effective (Department of Defense, 2013). The SVR defines the degree to

which the system meets performance specification (Department of Defense, 2013). Verification of the entire system happens when integration is achieved (Department of Defense, 2013). Sequentially upper-level systems elements are verified prior to transition into the next integration level (Department of Defense, 2013). The verification process output supports the Initial Operational Test and Evaluation (IOT&E) (Department of Defense, 2013).

2.2.1.2.7 Validation Process

The validation process provides evidence that the capability offered by the system fulfils performance requirements of the stakeholders and attains its usefulness in the planned operational environment (Department of Defense, 2013). Validation comprises assessing how effective, suitable, sustainable and survivable the operational system and its elements are under realistic operational conditions (Department of Defense, 2013). The validation process is usually conducted by independent testers (Department of Defense, 2013). The system end users and stakeholders are usually involved in validation activities (Department of Defense, 2013).

Validation activities may be executed in planned environment of operation or simulated environment using mock-ups, prototypes, models or simulations (Department of Defense, 2013). Early rigorous execution of validation considerably reduces risk by detecting issues before hand (Department of Defense, 2013). This improves performance of the system at the final validation stage (Department of Defense, 2013). The output of the validation process is a validated system and elements which result to Full-Rate Production (FRP) and full deployment decision review (Department of Defense, 2013).

2.2.1.2.8 Transition Process

Transition is the process implemented to transfer any system element to the next level in the physical architecture (Department of Defense, 2013). With respect to the end-item system, it involves installing and fielding the system to the end user in its operational environment (Department of Defense, 2013). Planning for system transition early decreases risk and facilitates easy delivery and speedy acceptance by the end user (Department of Defense, 2013).

Considerations of transition include user requirements, deployability, training, handling and transportation, among others. The process also makes sure that each site is adequately prepared to receive, accept and install the system as applicable (Department of Defense, 2013). The process involves activities of maintaining and supporting the deployed system, and also reporting and solving inadequacies (Department of Defense, 2013). Transition activities

differ depending on the scale of the program, complexity of the system and phase in life cycle (Department of Defense, 2013). When the end user system requires integration with other systems in the operational environment, the transition process is conducted together with the integration and interface management processes to ensure easy transition (Department of Defense, 2013).

2.3 Defense Acquisition

The Department of Defense (DoD) achieves acquisition of new weapons for defense forces through the Defense Acquisition System (Government Accountability Office, 2017). The system involves defense acquisition programs proceeding through different development phases (Government Accountability Office, 2017). New product development is challenging in any field and is particularly difficult in the defense sector because it involves interactions between industrial suppliers and several government entities trying to balance competing objectives (Cilli, Parnell, Cloutier, & Zigh, 2016). Decisions in the defense sector are made in an environment with high stakes, accountability, and uncertainty (Cilli, Parnell, Cloutier, & Zigh, 2016). (Cilli, Parnell, Cloutier, & Zigh, 2016) states that the defense acquisition system must deliver more inexpensive systems as a matter of national security. The defense acquisition system, in spite of its limitations has created several weapons that have performed well in battle. During execution of a new process, early identification of gaps likely to arise in defense acquisition is crucial (Cilli, Parnell, Cloutier, & Zigh, 2016).

2.3.1 Defense Acquisition Lifecycle

The defense acquisition life cycle is represented by the Defense Acquisition System (Bogan, Percy, & Kellerman, 2017). The life cycle process is made up of *phases*, which are separated by decision points called *milestones* (Defense Acquisition University, 2003). The criteria for entry for each phase guide the Milestone Decision Authority (MDA) to determine the proper point for a program to enter the acquisition process (Defense Acquisition University, 2003). The milestones present the framework with which program managers and MDAs can evaluate acquisition programs, monitor progress, detect obstacles, and make corrections (Defense Acquisition University, 2003). The MDA approves appropriate phase entry after completing a successful review by signing an Acquisition Decision Memorandum (Defense Acquisition University, 2003). As illustrated in Figure 2, the Defense Acquisition System comprises five phases and three milestones (Bogan, Percy, & Kellerman, 2017). The following section describes each of the life cycle phases in detail.

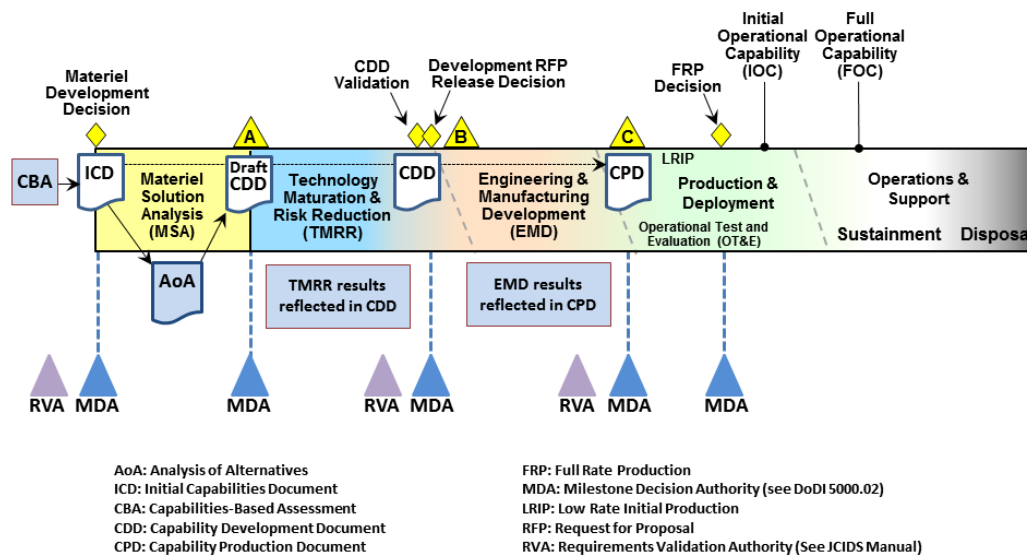


Figure 2: The Defense acquisition system (Department of Defense, 2013)

2.3.1.1 Pre-Materiel Development Decision

The Pre-Materiel Development Decision (MDD) phase aims to gain understanding of the needs of the user, obtain practical materiel solution approaches, and establish a plan for the next acquisition phase (Department of Defense, 2013). This phase supports the beginning of Analysis of Alternatives (AoA) and the information obtained guides the MDA to approve entry into acquisition life cycle and to undertake a materiel solution (Department of Defense, 2013).

Development planning (DP) consists of technical activities that enable informed decisions to be made on the direction that a materiel development takes to meet operational needs (Department of Defense, 2013). Activities of DP start before the Materiel Development Decision and continue throughout the Materiel Solution Analysis (MSA) phase (Department of Defense, 2013). The effort ends upon completion of a successful MDD review where the MDA authorizes entry into the Defense Acquisition System (Department of Defense, 2013). The decision is reported in an Acquisition Decision Memorandum which states the authorized point of entry, generally the MSA phase (Department of Defense, 2013). Before entry into the Defense Acquisition System, all potential materiel solutions undergo an MDD. The MDD technical plan and budget should reveal the activities needed in the next phase (Department of Defense, 2013).

2.3.1.2 Materiel Solution Analysis Phase, and Milestone A

The acquisition process officially starts with the Materiel Solution Analysis (MSA) phase. The objective of this phase is to identify and describe a chosen materiel solution to address user capability gap (Department of Defense, 2013). The MSA phase involves two main activities; AoA and post-AoA operational analysis and concept engineering (Department of Defense, 2013). An AoA evaluates several possible materiel solutions with respect to performance, cost and risk, guided by the AoA guidance and study plan (Department of Defense, 2013). The findings facilitate development of technical performance requirements needed at the next milestone, Milestone A. These requirements are a foundation for the specification of system performance for the next phase and also help alleviate risk in the next phase (Department of Defense, 2013).

In the MSA phase, the component combat developer prepares a Concept of Operations (CONOPS) reliant on validated capability requirements document (Department of Defense, 2013). The CONOPS consists of tasks, durations, and operating environment for the selected materiel solution to perform missions (Department of Defense, 2013). It advises MSA phase activities and plans for the next phase (Department of Defense, 2013). The technical review performed in the MSA phase is the Alternative Systems Review (ASR) (Department of Defense, 2013). The MSA phase starts after a positive MDD review has been conducted and ends when phase-specific entry criteria for the next milestone has been met (Department of Defense, 2013).

2.3.1.3 Technology Maturation and Risk Reduction Phase, and Milestone B

The acquisition process moves into the Technology Maturation and Risk Reduction (TMRR) phase to establish a strategy that makes sure that the requirements are affordable and technically feasible (Bogan, Percy, & Kellerman, 2017). The TMRR phase aims to decrease technical risk and gain more knowledge of the materiel solution to enable sound investment decisions at the Engineering and Manufacturing Development (EMD) review and Milestone B on whether to commence an acquisition program (Department of Defense, 2013). The main efforts in this phase include: determining suitable technologies for the whole system; maturing the technologies; prototyping the system and its elements; developing a pilot design; carrying out trade studies and refine requirements and designs; and executing suitable development activities (Department of Defense, 2013).

The program team employs approaches such as research and competitive prototyping in combination with technology readiness levels (TRL) to evaluate the technology maturity

(Department of Defense, 2013). The systems engineer conducts technical review and audits to assess if the aimed technical maturity points are reached as the system matures (Department of Defense, 2013). The technical reviews performed in the TMMR phase include System Requirements Review (SRR), System Functional Review (SFR), Software Specification Review (SSR), and Preliminary Design Review (PDR). The outputs of this phase motivate the recommendation at Milestone B that an appropriate solution with tolerable risk and complexity has been found (Department of Defense, 2013). The phase starts when a positive Milestone A decision has been made and ends with a successful Milestone B decision (Department of Defense, 2013).

2.3.1.4 Engineering and Manufacturing Development Phase, and Milestone C

The acquisition process continues to the Engineering and Manufacturing Development (EMD) phase, which designates the beginning of an actual acquisition program (Bogan, Percy, & Kellerman, 2017). The primary goal of this phase is to develop the preliminary product baseline, verify that it meets the functional and allocated baselines, and convert it into a producible design (Department of Defense, 2013). It involves technical evaluation and controls efforts to reduce risks and meet system cost, performance and schedule objectives (Department of Defense, 2013).

The major reviews in the EMD phase are the Critical Design Review (CDR) and Production Readiness Review (PRR). The CDR evaluates maturity of the design by showing that it fulfills the components of the CDD (Bogan, Percy, & Kellerman, 2017). The PRR decides if the system design and manufacturer are set to enter the phase of production with tolerable risk (Bogan, Percy, & Kellerman, 2017). The technical review criteria assure that the system design and development have matured and can support commencement of the Production and Development phase (Department of Defense, 2013).

The EMD phase activities include: establishing the preliminary product baseline, determining subsequent steps on configuration changes, and accepting system deliveries (Department of Defense, 2013). Outputs assist technical suggestion at Milestone C that the maturity of manufacturing processes is sufficient to support Low Rate Initial Production (Department of Defense, 2013). Activities of the EMD phase start after a positive decision has been made at Milestone B and ends with a successful Milestone C decision (Department of Defense, 2013). The acquisition process then enters the next phase (Production and Deployment phase).

2.3.1.5 Production and Deployment Phase

The goal of the Production and Deployment (P&D) phase is to provide validation of the product design and ensure delivery of the system's quantity needed for maximum operating capability (Department of Defense, 2013). The major efforts involved in this phase are Low-Rate Initial Production (LRIP), Operational Test and Evaluation (OT&E), Full-Rate Production (FRP) and Full Deployment (FD) (Department of Defense, 2013).

Development of manufacturing should be finished at Milestone C, however additional unexpected development of manufacturing process and testing may be needed for improvements and redesigns (Department of Defense, 2013). At the end of LRIP, development of manufacturing should be finalized, and no substantial risks carried into FRP (Department of Defense, 2013). Readiness for OT&E assesses the maturity of the system (Department of Defense, 2013). The P&D phase activities start when a successful Milestone C decision is made and ends when Full-Operational Capability (FOC) is obtained (Department of Defense, 2013). They facilitate transition of the program in to full operations and sustainment.

2.3.1.6 Operations and Support Phase

The purpose of the Operations and Support (O&S) phase is to implement a support program that fulfils the system performance requirements and cost-effectively sustains the system throughout its life cycle (Department of Defense, 2013). This phase overlaps with the P&D phase. Planning for this phase is documented in the Life-Cycle Sustainment Plan (LCSP) and starts in the MSA phase, through to the EMD phase (Department of Defense, 2013).

The two key efforts in this phase are life cycle sustenance and disposal (Department of Defense, 2013). During sustenance of the life cycle, activities include evaluation of Environmental Safety and Occupational Health (ESOH), technology refresh, modification of life-extension (Department of Defense, 2013). Disposal deals with when the system does not deliver an operative or efficient capability to the defense forces any more, and the Department then decides whether to modify or dispose of it (Department of Defense, 2013). Activities in the O&S phase commence when system is deployed and ends when a system is demilitarized and disposed of (Department of Defense, 2013).

2.4 Applying Systems Engineering in Defense Acquisition

In defense acquisition, it is critical to apply rigorous and effective engineering processes to ensure development of affordable and sustainable operational weapon systems (Defense

Acquisition University, 2010). Systems engineering provides the technical structure for capability delivery to the defense forces (Department of Defense, 2013). It facilitates integration of the required operational capabilities into the system design; integrates technical efforts associated to manufacturing, verification, deployment and operations; and generates reliable technical information to guide the decision-making process (Defense Acquisition University, 2010). The U.S DoD defense acquisition system was revised to increase emphasis on systems engineering activities to be incorporated early in the lifecycle (Cilli, Parnell, Cloutier, & Zigh, 2016).

Application of systems engineering reduces risk and enhances technical performance (Kludze, 2003; (Componation, Dorneich, & Hansen, Comparing systems engineering and project success in commercial-focused verses government-focused projects, 2015)). Programmatic and technical risks can be applied to assist with prioritizing which systems engineering processes to use (Componation, Dorneich, & Hansen, Comparing systems engineering and project success in commercial-focused verses government-focused projects, 2015). Significant relationships have been found between effective system engineering and the performance of programs (Elm & Goldenson, 2012; Componation, Dorneich, & Hansen, Comparing systems engineering and project success in commercial-focused verses government-focused projects, 2015). The DoD recommends application of a systems engineering approach to manage acquisition programs to optimize total system performance and minimize total ownership costs (Department of Defense, 2013). Systems engineering should be implemented throughout the life cycle of the system (Defense Acquisition University, 2010). The following section discusses application of systems engineering in each of the phases of the defense acquisition life cycle.

2.4.1 Pre-Materiel Development Decision Phase

Applying systems engineering processes during the early phases in acquisition ensures that program capabilities meet their time and budget goals (Department of Defense, 2013). Pre-MDD phase effort reduces the feasible solutions to a practical set through early constraint identification and technical feasibility analysis (Department of Defense, 2013). In feasibility analysis, programs with a wider range of alternatives have better cost and schedule outcomes compared to those with narrow range of alternatives (Department of Defense, 2013).

Systems engineering activities in the pre-MDD phase include: obtaining a detailed understanding of the capability gap and identify sources of the gap; finding a range of possible materiel solutions to satisfy the need; identifying near-term prospects for speedy response to the capability need; collaborating with other teams to build technical knowledge for potential

materiel solutions to include experimenting and prototyping; evaluating trade space to ascertain performance and cost benefits of potential solution; planning for technical efforts needed in the next phase; carrying out early risk analysis of the alternatives to be evaluated during the next phase; and ensuring quality of operational requirements (Department of Defense, 2013). The systems engineer should engage the end user as much as possible in this phase.

2.4.2 Materiel Solution Analysis

Systems engineering activities in this the MSA phase results in development of an operational system architecture and an initial specification of system performance (Department of Defense, 2013). Participation of the systems engineer in AoA enables evaluation of performance and feasibility, and optimization of alternatives (Department of Defense, 2013).

In the MSA phase, SE address numerous planning elements such as system concept, acquisition, engineering, test and evaluation approaches, schedule and risk (Department of Defense, 2013). Systems engineering activities involved in the MSA phase include: managing the implementation of the phase technical activities; determining and tracking the technical maturity of the system; identifying technologies to include in technical risk assessment; conducting trade studies; developing performance specification of the system; developing technical plans and approaches and documenting them in the SEP; ensuring that the technical phase elements are reliable and support the next phase (Department of Defense, 2013). The knowledge obtained in this phase offer assurance that approach of the technically feasible solution is affordable, has acceptable risk and is in line with the user needs (Department of Defense, 2013). Systems engineering offers a foundation for planning and execution of the TMRR phase (Department of Defense, 2013).

2.4.3 Technology Maturation and Risk Reduction

In the TMRR phase, systems engineering involves applying a prototyping system strategy that balances capability needs and design consideration (Department of Defense, 2013). The prototyping should emphasize risk reduction and competition, and the prototyped solutions should be assessed against cost, performance and schedule constraints of the system (Department of Defense, 2013). This informs a basis for finalizing the specification of system performance.

Systems engineering activities in the TMRR phase include but are not limited to: supervising and establishing technical tasks as highlighted in the SEP; conducting technical reviews; evaluating and monitoring program maturity using technical performance parameters;

performing rigorous evaluation of technical risk; supporting Technical Readiness Assessment (TRA); and maintaining oversight of the development process of the system. The systems engineer helps to produce a pilot system design with an adequate system maturity level to ensure entry into the next phase with low risk EMD (Department of Defense, 2013).

2.4.4 Engineering and Manufacturing Development

In the EMD phase, the major areas of focus for systems engineering are finalizing the elaborate system build-to design, building the preliminary product baseline, integrating and testing the system and its elements, proving maturity and readiness of the system to start production for operational and sustainment activities (Department of Defense, 2013).

SE activities in the EMD phase include among others: realization of the system architecture; maturing system design using prototypes; developing the initial product baseline and stable design; preparing for production; building, integrating and testing the system elements; integrating and verifying system compliance; and addressing problem reports. As the system and its elements mature, the systems engineer employs audits and technical reviews to determine if the technical maturity points are reached as the acquisition life cycle continues (Department of Defense, 2013).

2.4.5 Production and Deployment

Systems engineering in the P&D phase provides the product baseline, and supports deployment and adaption of a capability to the end users, defense forces and associated organizations (Department of Defense, 2013). The systems engineer ensures that the system is ready to enter Operational Test and Evaluation (OT&E) phase. The SE activities involved in the P&D phase are to: ensure a successful Full Operational Capability (FOC); mature the procedures for production, manufacturing and deployment; respond to inefficiencies and establish actions of correction; support system performance validation related to OT&E; validate the production configuration before Full-Rate Production (FRP) or Full Deployment (FD) (Department of Defense, 2013).

The responsibilities of the systems engineer include to: analyse deficiencies from OT&E; conduct risk assessments and risk mitigation activities; continue performing trade studies to identify the best cost-effective process; establish strategies to validate manufacturing processes; evaluating the achievability of full-rate production; update production costs; support technical reviews, production schedule and materiel readiness activities, among others. When the service lives of DoD weapon systems are prolonged, the challenge of Diminishing Manufacturing Sources and Materiel Shortages (DMSMS) arises. The systems

engineer should plan for possible impacts of obsolescence in the P&D and O&S phases (Department of Defense, 2013).

2.4.6 Operations and Support

Systems engineering in the O&S phase involves evaluating if the deployed system and its elements still deliver the required capability in a manner that is safe, cost effective and sustainable (Department of Defense, 2013). Systems engineering efforts include collecting data, evaluation, and corrective actions to ensure operational suitability and effectiveness of the system (Department of Defense, 2013).

System engineering activities in the O&S phase include: improving the maintenance program to reduce life-cycle costs; performing engineering inquiries and assessing user feedback; developing corrective actions from end user feedback; performing ESOH risk assessments; mitigating possible obsolescence impacts; and updating system certifications (Department of Defense, 2013). Engineering analysis identifies possible obsolescence impacts in both the P&D and O&S phases (Department of Defense, 2013; Department of Defense, 2013).

2.5 The Challenges facing Defense Acquisition Projects

The defense sector is particularly challenging, and decisions have to be made in an environment with high stakes and uncertainty (Cilli et al., 2015). According to the Quadrennial Defense Review, the four major challenges that affect the DoD's acquisition of military capabilities include; limitations of current technology for new systems and increase of requirements during the life cycle (requirements creep); lack of trained personnel in the areas of systems engineering, cost estimation and acquisition management; underestimation of cost during the acquisition process; and inefficient and ineffective delivery of logistical support to defense forces in the field (Defense Acquisition University, 2010).

The challenges facing defense acquisition programs are generally related to technical complexity, talent shortage, supply chain challenges, program management challenges, and politics (Deloitte, 2009). These result in cost overruns and schedule delays (Deloitte, 2009). The problems of cost overruns and schedule delays are discussed further discussed in the following section.

2.5.1 Cost Overrun

Cost overrun is a major problem facing many defense acquisition programs. Cost growth in acquisition programs has been attributed to requirements changes and lack of rigor and discipline in defining and understanding the initial requirements of a program (Government Accountability Office, 2016). Inadequately defining program requirements leads to cost growth and problems during weapons system development (Government Accountability Office, 2015). According to (Young, 2014) the causes of cost performance issues in defense acquisition include; escalating complexities of systems, lack of execution of systems engineering principles, prolonged systems life cycles, unstable funding & misappropriation of funds, and poor management capabilities (Young, 2014).

Defense acquisition programs have experienced cost overrun over the past years. For example, in 2016, the U.S DoD expected to invest \$1.4 trillion in developing and procuring major defense acquisition programs. However, an estimated 48% cost growth was experienced in delivery of initial capabilities (Government Accountability Office, 2016). In the following year (2017), the DoD acquisition programs experienced cost growth of over \$484 billion, with 60% of this occurring after programs began production (Government Accountability Office, 2017). Although the DoD's portfolio increased from 78 programs in 2016 to 79 programs in 2017, the cost estimate increased by \$9.4 billion to \$1.46 trillion (Government Accountability Office, 2017). Of the 78 programs assessed, 46 programs had \$26.8 billion in cost increases. Costs related to development experienced \$3.7 billion increase and the three major programs that accounted for this increase were the Evolved Expendable Launch Vehicle, the Littoral Combat Ship, and the Next Generation Operational Control System (Government Accountability Office, 2017). Procurement cost also increased by \$5.6 billion, with the biggest increase experienced in the shipbuilding program (Government Accountability Office, 2017).

Challenges in technical complexity of programs increase cost overruns (Deloitte, 2009). In 2007, technical complexity increased costs by 8.7% of the initial budget, accounting for 26% budget overrun (Deloitte, 2009). This is because more complex technologies require greater integration and interoperability (Deloitte, 2009). According to GAO (2015), acquisition programs face cost and schedule problems due to inability to make appropriate trade-offs during system development. In an effort to meet the challenging system requirements, programs end up making technical changes to the weapon system (Government Accountability Office, 2015). These cost growths are due to lack of systems engineering (Government Accountability Office, 2015). Systems engineering introduce rigor and discipline

to define and understand the initial requirements of a program thereby reducing risk (Government Accountability Office, 2016).

2.5.2 Schedule Delay

The costs of weapons and services required for national security, and the time to deliver them have continued to increase despite the many studies that have been done (Gansler, 2011) (Gansler, 2011; Cilli et al., 2015). In addition to cost issues in defense acquisition, there is also a dramatic increase in the development time of major weapons systems (National Research Council, 2008) (Board et al., 2008; Cilli et al., 2015). Schedule delays have been attributed to inadequately understanding the initial requirements of the program and requirements changes, also known as requirements creep (Government Accountability Office, 2016). The development time needed by recent programs is higher than those of historical programs by one to three times (Cilli et al., 2015).

In 2008, a study by the GAO on 95 weapons system programs of the DoD found that the average schedule delay was 21 months (Deloitte, 2009). In 2016, schedule delays of up to 30 months were experienced by defense acquisition programs in delivery of initial capabilities (Government Accountability Office, 2016). In 2017, of the 78 programs in the DoD 2016 portfolio, 11 programs experienced schedule delays, seven of which had a delay of 6 months or more (Government Accountability Office, 2017). One program, the Remote Minehunting System program had a significant delay of 2.5 years (Government Accountability Office, 2017). There was a two month increase in the DoD's programs delay in delivering a capability in 2017 (Government Accountability Office, 2017).

Programs with significant schedule delays are reported by the DoD as a breach in program acquisition baseline (Government Accountability Office, 2017). Technical complexity increases schedule delays because of the use of more advanced materials which require more time for development, testing, and manufacture (Deloitte, 2009). Development cycles are shorter when weapons systems are less complex (Deloitte, 2009). Inability to make appropriate trade-offs during system development also contributes to schedule problems (Government Accountability Office, 2015). Cost growth is also attributed to the lack of systems engineering (Government Accountability Office, 2015).

2.6 The Causes of Failures in Defense Acquisition Projects

Failure of defense acquisition program presents a critical problem in acquiring defense forces capabilities (Bogan, Percy, & Kellerman, 2017). Many studies have attributed the cause of failure in defense acquisition to various factors. According to GAO (2015), the major reason programs produce poor outcomes or fail is because of approval of programs that lack adequate knowledge on the requirements and resources needed to implement them (Government Accountability Office, 2015). The result of poor outcomes was because military services start program with idealistic requirements, immature technologies, and overestimated cost and schedule budgets (Government Accountability Office, 2015). (Deloitte, 2009) also stated that DoD acquisition programs fail because of reliance on unreasonable cost and schedule estimations, unreasonable expectations of program performance, application of immature technologies, and changes to requirements amidst ongoing programs (Deloitte, 2009).

Generally, the major causes of failure in acquisition programs are related to changing requirements, immature technology, unstable budgets, budget-related activities, schedule-driven program, and risk underestimation (Bogan, Percy, & Kellerman, 2017). Poor systems engineering has also been highlighted as a cause for failure of defense acquisition programs. The presence of one or more of these causes lead to failure.

Changing requirements. This refers to inability to adequately control client-oriented requirements (Bogan, Percy, & Kellerman, 2017). It results from lack of rigor and discipline in defining and understanding the initial requirements of a program (Government Accountability Office, 2016). In many instances, the program moves on to the acquisition process at Milestone B when the requirements are not completely developed. Insufficiently defining program requirements leads to cost growth and schedule delays during weapons system. It also leads to cost estimation problems associated with cost growth. Unstable changing requirements is a negative factor that can cause program failure (Bogan, Percy, & Kellerman, 2017; Kim, Axelband, Doll, ..., & Shelton, 2015). Program requirements, both at high levels and lower levels need to be critically analysed using SE techniques (Government Accountability Office, 2015).

Immature technology. This often means inability to meet the appropriate technology readiness level at a specific milestone (Bogan, Percy, & Kellerman, 2017; Clowney, Dever, & Stuban, 2016). This problem usually arises from over ambitious and prolonged product development with numerous technical uncertainties and inadequate knowledge regarding risks in production and performance. The knowledge inadequacy is due to lack of timely and

disciplined SE analysis of the requirements of the weapon system before commencing system development. The inability to mature technology before beginning systems development results in acquisition of programs with considerable technical risk (Government Accountability Office, 2017).

Budget related activities (poor cost estimation). Are activities related to budget and cost estimation and management, and is one of the major causes of program failure in defense acquisition (Bogan, Percy, & Kellerman, 2017). This is usually as a result of inadequately trained personnel in the areas of cost estimation and acquisition management (Defense Acquisition University, 2010). Defense acquisition often supports cost estimates that are too optimistic resulting in underestimation of cost (Defense Acquisition University, 2010). This causes “too many programs chasing too few dollars” sometimes leading to termination and failure of programs (Defense Acquisition University, 2010).

Unstable budgets. This is often from the DoD taking up more programs with limited budget resources, which affects implementation. This indicates that programs receive insufficient funds, which causes instability in defense acquisition and affects program outcomes and can lead to program failure (Bogan, Percy, & Kellerman, 2017).

Schedule-driven programs. Programs face challenges of unreasonable milestone duration, schedule estimates and slow decision making (Bogan, Percy, & Kellerman, 2017). Defense acquisition programs also make over optimistic schedule estimates. Unrealistic schedule estimates are connected to immature technology because testing and production may be performed concurrently to meet deadlines (Government Accountability Office, 2016). This schedule pressure is a major cause of failed program in defense acquisition (Bogan, Percy, & Kellerman, 2017).

Risk underestimation. This refers to inability to adequately anticipate and conduct assessment of risk (Bogan, Percy, & Kellerman, 2017). It is not uncommon for programs to be approved without consideration of the resources and technologies required to execute them successfully (Government Accountability Office, 2016). High programmatic and technical risk affects performance of programs and may lead to failure. Risk underestimation connects to the other causes as risk relates to requirements, technology, cost and schedule (Bogan, Percy, & Kellerman, 2017).

Poor systems engineering. Programs that are started with inadequate systems engineering have poor outcomes (Government Accountability Office, 2017). For example, the F-35

Lightning II program which started with a single-step strategy with little systems engineering faced major schedule and cost problems (Government Accountability Office, 2016). Lack of systems engineering result to cost and schedule growth (Government Accountability Office, 2015). Systems engineering introduce rigor and discipline to define and understand the initial requirements of a program thereby reducing risk (Government Accountability Office, 2016).

Generally, the impact of program failure leads to loss of investment funds and also affects the other areas of acquisition (Bogan, Percy, & Kellerman, 2017; Clowney, Dever, & Stuban, 2016). Many times, a lot of funds (up to several billion dollars) are spent by the DoD on a program development before termination (Cilli, Parnell, Cloutier, & Zigh, 2016). For example, the Joint Standoff Weapon program terminated in 2017 after investment (Government Accountability Office, 2017). The opportunity cost of spending large amounts of money on failed programs is that the money could be used to increase the efficiency and timely delivery of better capabilities to the defense forces by superior programs (Cilli et al., 2016). Analysing the root causes of failure of acquisition programs helps the DoD to improve its acquisition process to satisfy both budget and defense force's needs. Lessons from failed programs should be used to improve the performance of future programs (Bogan, Percy, & Kellerman, 2017; Brady, 2015)

2.7 Past Attempts to Improve SE Performance in DA Projects

A successful defense acquisition program delivers an efficient, effective and affordable system to the end user (the defense forces) (Defense Acquisition University, 2010). The desirable outcome is a 'win-win' for all participants. To improve performance of systems engineering in defense acquisition, different methods and tools have been developed. The following section discusses certain tools for improving performance of SE in acquisition programs. Two selected tools will be discussed, the Friedman and Sage Framework and Agile Systems Engineering.

2.7.1 The Friedman and Sage Framework

This two-dimensional framework proposed by Friedman and Sage for systems engineering consists of a 9×3 matrix comprising nine broad systems engineering concept areas as rows, and three columns representing the domain of principal activity (Friedman & Sage, 2004). As depicted in figure 3, out of the nine concept areas, six represent the phases in the SE life cycle. These are:

- A. Requirements Definition and Management;
- B. Systems Architecting and Conceptual Design;

- C. Detailed System and Subsystem Design and Implementation;
- D. Systems and Interface Integration; E- Validation and Verification;
- E. System Deployment and Post Deployment.

The other three represent necessary process and systems management support and include: G- Life Cycle Support; H- Risk Management; and System and Program Management (Friedman & Sage, 2004).

Concept Domain	Responsibility Domain		
	- 1 - SE CONTRACTOR RESPONSIBILITY	- 2 - SHARED RESPONSIBILITY	- 3 - GOVERNMENT RESPONSIBILITY
A. Requirements Definition and Management			
B. System Architecture and Conceptual Design			
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration			
E. Validation and Verification			
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment/Management			
I. System and Program Management			

Figure 3: The Friedman and Sage framework of key systems engineering concepts and responsibilities (Friedman & Sage, 2004)

The nine selected concepts cover the critical systems acquisition life cycle processes. The three columns of the framework denote contractor, government and shared responsibilities (Friedman & Sage, 2004). Contractor responsibilities can be further broken-down into for-profit and non-profit contractor responsibilities. When many contractor and government agencies are involved, the concept of government and contractor require modification. This results in considerations for systems of systems or coalition of systems. The three columns are specific, but their nature vary depending on if the system being developed is a stand-alone or a system of systems. Therefore, the description of responsibilities in these columns may vary between acquisition of a systems of systems and stand-alone system (Friedman & Sage, 2004).

This SE framework is robust and appropriate to manage successful programs. This is because the framework is capable of identifying issues that impact SE and management across the different levels (product, process, and policy). It assesses SE practices in acquisition program. However, the limitation of this framework is that it assesses programs that have been done.

2.7.2 Agile Systems Engineering

Agility is the ability to competently response to increasingly unpredictable and uncertain operational environments (Dove & LaBarge, 2014). In the defense sector, agility can be applied for forces transformation, rapid acquisition and fast response capability (Dove & LaBarge, 2014). Agile systems are flexible systems that can be modified in response to changing user requirements after they are initially deployed (Haberfellner & de Weck, Agile SYSTEMS ENGINEERING versus AGILE SYSTEMS engineering, 2005). Three important elements that are essential include; flexibility of system elements, sensors to monitor extrinsic features, and a robust decision mechanism (Haberfellner & de Weck, Agile SYSTEMS ENGINEERING versus AGILE SYSTEMS engineering, 2005). An agile system typically concerns risk management and providing alternatives when the survival of the system is under threat (Dove & LaBarge, 2014).

Agile systems engineering is significant when the development and manufacturing environment has considerable uncertainties (Haberfellner & de Weck, Agile SYSTEMS ENGINEERING versus AGILE SYSTEMS engineering, 2005). The uncertainties may be related to among others, ambiguous consumer requirements, feasibility of new technology, and suitability of manufacturing processes. Uncertainties should be resolved prior to initiation of operations of the system (Haberfellner & de Weck, Agile SYSTEMS ENGINEERING versus AGILE SYSTEMS engineering, 2005). Agile SE can be improved with new functional capability, restructured, scaled up or down for delivery of a capability, or reshaped for compatibility with the changed environment (Schindel & Dove, 2016). To introduce agility into a systems engineering process, it is important to gain an understanding of how stable the requirements are, how the requirements change, and the cost of the requirements (Haberfellner & de Weck, Agile SYSTEMS ENGINEERING versus AGILE SYSTEMS engineering, 2005).

2.7.2.1 Agile Systems Engineering Action Model

Considerations have been made to establish a systems engineering approach that can show agility and at the same time meet the general SE objectives of efficacy and efficiency (Stelzman et al., 2010). The systems engineering action model was developed by

(Haberfellner, Nagel, Becker, Büchel, & von Massow, 2002). It is a general model that comprises principles and procedure for good systems engineering practice (Stelzmann, Kreiner, Spork, Messnarz, & Koenig, 2010). The agile principles applied to the model were those suitable for systems engineering. Figure 4 shows a revised version of the Agile Systems Engineering Action Model.

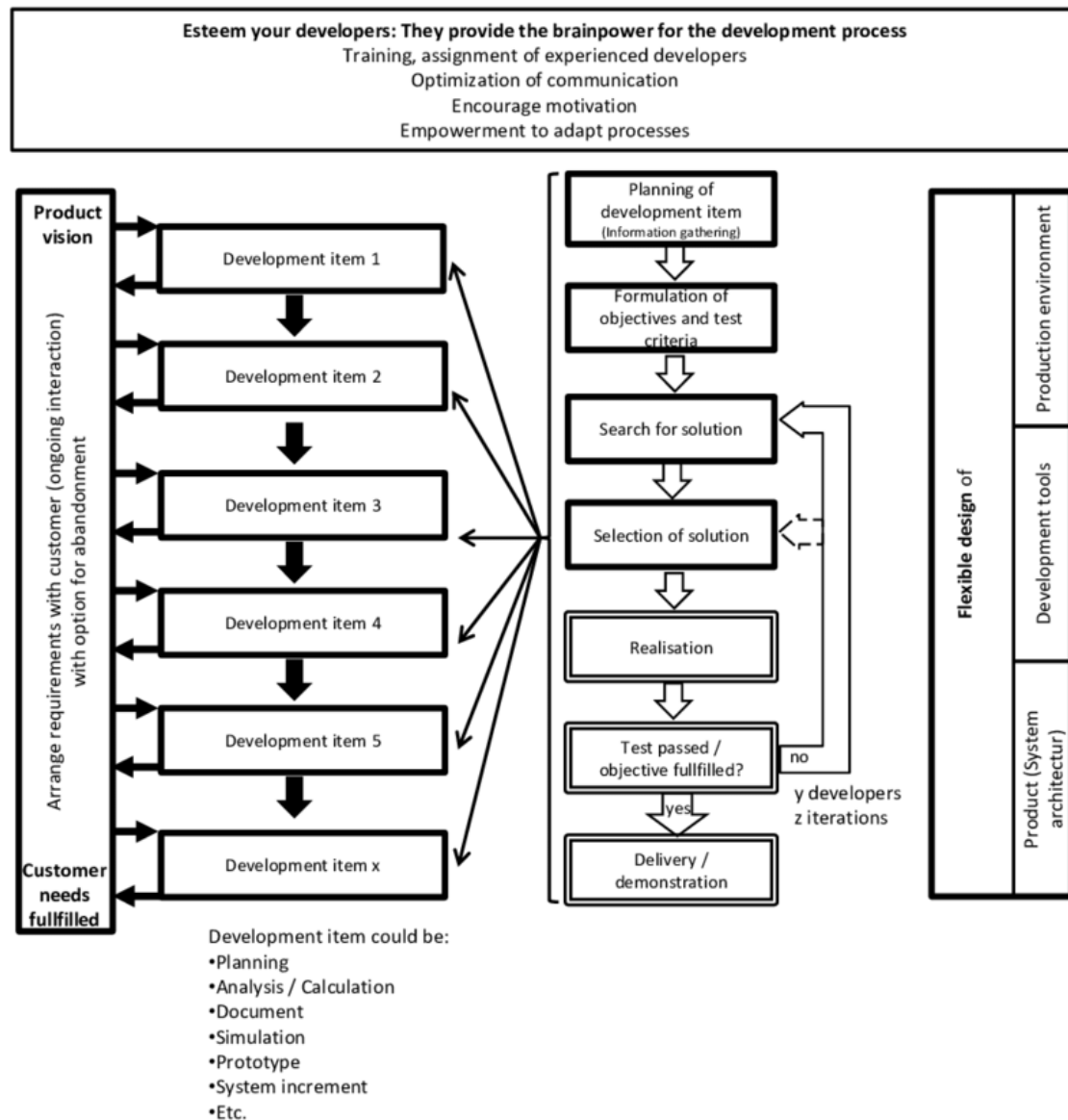


Figure 4: Agile Systems Engineering Action Model (Stelzmann, Kreiner, Spork, Messnarz, & Koenig, 2010)

The model entails four main principles.

- Esteem developers. This principle ensures that developers are treated appropriately. This is because more attention is usually given to processes. Since developers do the

work, they should be considered so that they do the job in the best way (Stelzmann, Kreiner, Spork, Messnarz, & Koenig, 2010).

- Incremental development with close user interaction. This principle suggests that not all requirements need to be specified at the start because some will change during development and just a vision of the product is enough at the start of the project. Items that require collection of information to understand the system should be established first (Stelzmann, Kreiner, Spork, Messnarz, & Koenig, 2010).
- Iterative development of increments. Each item is developed in iteration of the presented development cycle. It begins with planning (deciding what to develop, who, and how long), followed by formulation of elaborate objectives and criteria. The developers then develop parts and system increment is formed.
- Flexible design of products, development and production tools. This principle is critical for all changes as there should be flexibility for implementing changes. Principle 2 and 3 are significant for agile responses to changes that manifest as a result of information collected during development.

The model can be adapted to prevailing development processes to increase agility, and can also be applied to establish new processes that are agile without compromising good systems engineering practice (Stelzmann, Kreiner, Spork, Messnarz, & Koenig, 2010). Some parts of the model such as handling customers and flexible design are partially process areas but are far-reaching (Stelzmann, Kreiner, Spork, Messnarz, & Koenig, 2010). Agility and SE are not restricted to process management. Therefore, a comprehensive perspective was taken on system emerging companies to obtain additional starting points to facilitate agile behaviour within systems engineering (Stelzmann, Kreiner, Spork, Messnarz, & Koenig, 2010).

These frameworks can be employed to improve performance of SE not only in defense acquisition but other sectors too. However there remains a challenge as most tools that have been developed are used to assess systems engineering performance after a program has finished. Therefore, it is crucial to develop a tool to assess SE performance in defense acquisition during program execution where decisions can be made to overcome obstacles.

2.8 Summary

This chapter provided a detailed literature review analysis. The chapter began by providing an overview of systems engineering. It then discussed the systems engineering framework, detailing each of the technical management processes and technical processes of systems engineering. The chapter then explicitly discussed the defense acquisition life cycle, explaining each phase and milestone. It further discussed the application of systems

engineering at each of the phases of the defense acquisition life cycle. It then went on to discuss the challenges and causes of failure of defense acquisition programs. The chapter then concluded by examining past attempts at improving systems engineering performance in defense acquisition by looking at two systems engineering tools.

3 RESEARCH METHODOLOGY

3.1 Introduction

Several research methods can be used in systems engineering and these depend on the research questions, objectives and context of the study. Selection of a research methodology is based on the suitability of the method for the research problem and question under study.

The purpose of this research is to investigate how performance of systems engineering can be improved during execution of weapon systems development projects.

This chapter presents a systematic description of the methodology used in the study. The chapter describes the research philosophy and underpins the study in the interpretivist paradigm. The chapter presents the research approach and research strategy adopted in the study. It further details the data collection technique and data analysis method employed in the study, and finally addresses the issue of authenticity and trustworthiness. The motivation for the selected research methodology is also discussed in this chapter.

3.2 Research Philosophy (Research Paradigm)

A paradigm is a particular way of thinking that represents the values and beliefs in a discipline and guides the way problems are solved (Schwandt, 2001). A paradigm facilitates asking certain questions and the use of suitable approaches to systematic inquiry, also known as methodology (Chilisa & Kawulich, 2012). Certain methodologies may be associated with specific paradigms (Chilisa & Kawulich, 2012). For instance, quantitative methodology is commonly used in a positivist paradigm while the constructivist and interpretative paradigms mostly use qualitative methodology (Chilisa & Kawulich, 2012). However, this is not universal as sometimes quantitative methodology may be used in interpretative study (Chilisa & Kawulich, 2012). Some methods such as case study and action research can be used in

interpretive, positivist or critical paradigms, although there may be contentions in some cases (Ogunleye, 2017; Walsham, 1995).

A number of paradigms have been proposed but they can all be placed into three main groups, namely positivist, interpretivist, and critical paradigms (Kivunja & Kuyini, 2017; Candy, 1989). Other paradigms include post-positivist, pragmatist, critical realism (Oates, 2005), transformative and postcolonial indigenous paradigms (Chilisa & Kawulich, 2012).

Positivist paradigm considers science as the only foundation of true knowledge and that the only way to establish truth and objective reality is by the scientific method (Chilisa & Kawulich, 2012). Research located in this paradigm uses deductive logic, hypothesis formulation and testing, calculations, operational definitions, mathematical equations and extrapolations to draw conclusions (Kivunja & Kuyini, 2017). In other words, positivist research uses measurable variables to characterise the phenomenon and denotes that reality can be explained by quantifiable properties that are not dependent on the observer or the instruments used by the observer (Myers, *Qualitative Research in Information Systems*, 1997). It aims to make explanations and predictions based on measurable outcomes (Kivunja & Kuyini, 2017). In positivist research, emphasis is on quantitative data and the researcher is independent of the research phenomenon (Orlikowski & Baroudi, 1991).

Interpretivist/constructivist paradigm is based on understanding the subjective world of human experience (Guba & Lincoln, *Fourth generation evaluation*, 1989; Kivunja & Kuyini, 2017), and that truth lies within human experience (Chilisa & Kawulich, 2012). The interpretivist paradigm believes that knowledge or reality is subjective because it is mind dependent and socially constructed (Chilisa & Kawulich, 2012), and is why this paradigm is sometimes called the constructivist paradigm (Kivunja & Kuyini, 2017). Focus is placed on understanding the viewpoint of the observed subject instead of the observer's viewpoint (Kivunja & Kuyini, 2017). It does not predefine variables, and the researcher aims to understand the phenomenon in its context (Chilisa & Kawulich, 2012). In this paradigm, theory follows research and is grounded in the generated data (Kivunja & Kuyini, 2017). The purpose is to understand the experiences of people and the research is conducted in the natural setting of the participants (Chilisa & Kawulich, 2012). The designs commonly used in this research paradigm are ethnography, grounded theory, biography, phenomenology and case study (Creswell, *Research design: Qualitative, quantitative, and mixed methods approaches*, 2014). The data collections techniques include interviews, documents, observations, visual aids, drawings, photographs and artefacts (Chilisa & Kawulich, 2012).

Critical/ transformative paradigm bases its research on issues of social justice and aims to address issues that result to social oppression, struggles, conflict and power structures at any level they might occur (Kivunja & Kuyini, 2017). It focuses on oppositions and is emancipatory that is, it seeks to eliminate causes of alienation and domination. This paradigm is influenced by philosophies and theories whose common theme is to emancipate and transform communities through group action (Mertens, 2009). The goal of transformative research is to destroy illusions, myths and false knowledge so as to empower people to act and transform society (Chilisa & Kawulich, 2012). Some theories in this paradigm include Marxism, Freirian theory, feminist theories and race-specific theory, among others. Both qualitative and quantitative methods are used in the critical research paradigm (Chilisa & Kawulich, 2012). Designs commonly applied include action research and participatory rural appraisal approach (Chilisa & Kawulich, 2012).

An interpretivist research paradigm was adopted in this study.

3.2.1 Interpretivist research paradigm of the study

The research aims at investigating how systems engineering performance can be improved in defense acquisition projects. The interpretive research approach was adopted as suitable to investigate whether systems engineering is adequately implemented in defense acquisition projects and how SE performance can be improved during execution of these projects. In the context of this study, the interpretivist research paradigm was adopted as the appropriate because its methodology and method of data collection will facilitate the collection and analysis of data that is essential in investigating the research question of the study.

Since systems engineering involves not only technical aspects but also social aspects, the interpretive research is suitable. Furthermore, given that most defense acquisition projects are usually complex, interdisciplinary and large, qualitative research is appropriate for this study. (Boucaut, 2001) supports this notion by highlighting that qualitative research is an advantageous method for complex situations.

Adopting the interpretive research approach was beneficial in the following ways:

- To study participants/ projects in their natural settings. In this case it involved gathering material in the natural contexts i.e. project documents. Investigating participants outside the natural setting results in findings that are out of context.
- To observe, capture and explain behaviour of participants/ projects, in this context weapon systems development projects.
- To permit comprehensive analysis of the case studies.

The interpretivist paradigm focuses more on relevance other than rigor (Ponelis, 2015). This will enable gaining an understanding of systems engineering performance in the context of defense acquisition projects.

The following section revisits the research questions formulated in the study.

3.3 Research Questions

The main purpose of this research was to understand the performance of systems engineering in defense acquisition projects and how systems engineering performance can be improved. When formulating the research question, it is important to also consider the social nature of systems engineering. This is because systems engineering is an interdisciplinary field, where the researcher studies systems engineering and also integrates the organisation so as to benefit the entire system (which encompasses the technology, people, organisation and the society that deploys the technology for use).

This study comprised one main research question and four sub-questions. The main research question is:

How can performance of systems engineering in weapon systems development projects be improved?

The research sub-questions of the study are:

1. Are systems engineering activities adequately implemented in defense acquisition projects?
2. What are the challenges that face defense acquisition projects?
3. Why do most of the defense acquisition projects fail to meet the cost and time constraints?
4. How can systems engineering performance be improved during the execution of defense acquisition projects?

The research questions of the study enabled the researcher to obtain data within the scope of the questions. The research questions were investigated using a qualitative background, using multiple case study involving three systems engineering case studies executed according to the DOD systems engineering model. The purpose of this thesis, therefore, is to create a better understanding of how performance of systems engineering can be improved in the context of weapon systems development.

3.4 Research Approach

This study followed a qualitative research approach. Qualitative research is a systematic scientific inquiry that aims to develop a holistic, mostly narrative description that informs the understanding of a phenomenon (Astalin, 2013). It seeks to understand a phenomenon in-depth and within specific contexts (Chism, Douglas, & Hilson, 2008). (Chism, Douglas, & Hilson, 2008) state that “the key characteristics of qualitative research are an in-depth focus on only a few individuals or situations, focus on the context of the study, and recognition of the researcher as an instrument of the study”.

Systems engineering, according to (Muller, 2013) is “a young discipline that is mostly practiced in the field”, and most systems engineers base on experience to perform their work. Although systems engineering is a typically technical field, its effectiveness largely depends on human aspects (Muller, 2013). It is a mix of both hard engineering and soft human factors, and the softer factors significantly affect the research approach (Muller, 2013). Research in systems engineering builds on existing scientific methods, both technical and also social sciences (Muller, 2013). Therefore, both quantitative and qualitative research are applicable in systems engineering.

Qualitative research differs from quantitative research in its assumptions, approach and outcomes (Chism, Douglas, & Hilson, 2008). While quantitative research aims at identifying what the occurrence is in terms of context-free generalisations, qualitative research seeks to understand why or how a phenomenon occurs in a specific context (Chism, Douglas, & Hilson, 2008). Qualitative analysis involves analysing observations without the use of numeric methods or coding to quantitative scales (Bengtsson, 1990). It is instead based on the experiences of the observer, context of observations and rational argumentation (Bengtsson, 1990). It involves using various experimental material such as interviews, introspective reflections, observation, document reviews, experiences, etc..

Research in engineering is usually grounded in the positivist paradigm with the application of quantitative research methodology and methods (Kelly & Bowe, 2011). However, when engineers are required to solve a problem or design an artefact, then qualitative research may be appropriate (Kelly & Bowe, 2011). This justifies the selection of the qualitative research approach in this study. The adoption of a qualitative research approach enabled attainment of a good understanding of the performance of systems engineering in the context of weapon systems development, and enabled development of an assessment tool to be implemented during execution of systems engineering in weapon systems development projects.

3.5 Research Methodology

The research process of this study was conducted using case studies and document analysis to investigate the research questions so as to achieve the research objectives. The case study method aims to answer the 'how' and 'why' questions and therefore suitable for descriptive and exploratory studies (Mouton, 2001; Myers, Qualitative research in business and management, 2009). The following sections describe the research techniques and methodologies used in the study.

3.5.1 Research Strategy: Case Study

The research strategy adopted in this study is the case study. Case study as a qualitative inquiry of a clearly defined system or multiple systems using multiple information sources such as observations, interviews, documents and artefacts (Creswell, Qualitative inquiry & research design. Choosing among five approaches, 2007). Case study research aims to gain an in depth understanding of a case in its natural setting, and acknowledges the complexity within the context (Battisto & Franqui, 2013). The three types of case studies are intrinsic, instrumental, and collective (Creswell, Qualitative inquiry & research design. Choosing among five approaches, 2007). The intrinsic case study focuses on the case itself due to its unusual or unique nature. The instrumental case study focuses on a concern or an issue and then chooses one bounded case to demonstrate a case description. The collective case study uses the replication logic by employing multiple bounded cases to identify case-based themes (Creswell, Qualitative inquiry & research design. Choosing among five approaches, 2007; Battisto & Franqui, 2013). For this study, the collective case study was used. It involved using multiple case studies to identify common systems engineering practices that result in success or failure of weapon systems development projects.

Case-based evaluations are applicable in cases where there are very few cases to conduct quantitative analysis (Simister, 2017) and also when evaluating complex interventions (Stern, et al., 2012), as is the case with weapon systems development projects. They are also employed when focus is on causal analysis (Simister, 2017). Therefore, this method is appropriate for the study because weapon systems development projects are complex in nature, focus is on causal analysis, and the study focuses on drawing lessons from cases.

Multiple case studies study several cases to understand the differences and similarities among the cases (Baxter & Jack, 2008; Stake, The art of case study research, 1995). Also, the

researcher can analyse data within each situation and across situations (Yin, 2003). Case studies have a dual purpose of being study units of their own and also larger groups of units (Gerring, 2004), and are often used when it is difficult to obtain a precise solution. (Gustafsson, 2017). (Baxter & Jack, 2008) state that the evidence generated from multiple case study is strong and dependable, and the study is regarded as more robust. This, therefore, motivated the use of multiple case study in this research.

Adoption of cross-case analysis enables comparison of multiple cases divergently which would be impossible in single case analysis (Oyomno, 2013). Case comparison can be used to determine similarities, differences or to classify data according to data sources (Abrahamsson, 2002). (Eisenhardt, 1989) recommends use of cross-case analysis when searching for patterns. Cross-case analysis involves examining the data exhaustively and prevents obtaining premature conclusions as it requires the researcher to look at the data in several ways (Oyomno, 2013). Cross-case synthesis of multiple case studies involves treating each individual case study as separate study, creating word tables that display data from the individual cases according to some uniform framework, examining word tables for cross-case patterns, and relying strongly on argumentative and not numeric properties (Perry, Sim, & Easterbrook, 2004). The findings are stronger if the pattern from one type of data is confirmed by evidence from another (Oyomno, 2013). Hence the application of cross-case analysis in the study.

3.5.2 The Selection of Case Studies

Instead of representativeness, the criteria for selecting cases is relevance to the research questions (Carson, Gilmore, Perry, & Gronhaug, 2001). According to (Eisenhardt, 1989), “random selection of cases is neither necessary, nor even preferable”. When selecting suitable cases, preference is given to cases that provide rich information with regards to the topic under investigation, thus purposive and snowball sampling are justified (Patton, 2002).

This study used three case studies of weapon systems development projects. The cases were selected using purposive sampling as the appropriate method of sampling so as to choose cases with the most-rich information in order to answer the main questions, thus leading to a holistic analysis (Simister, 2017). Purposive sampling, also known as judgement sampling is a non-random sampling technique that involves deliberate selection of a sample or informant because of the qualities they possess (Oyomno, 2013). It does not require underlying theories or a specific number of samples or informants. Sample size in purposive sampling may or may

not be fixed before collection of data, and depends on available resources and objectives of the study (Oyomno, 2013). Although some studies recommended 4-10 cases for multiple case studies, many studies, with good reason, have fewer than four cases and more than 15 cases (Stake, Qualitative case studies, 2005). In this study, three systems engineering case studies were chosen based on weapon systems development projects that were contracted and executed according to the DOD systems engineering model. All the case studies are documented by the Centre of Systems Engineering at the Air Force Institute of Technology. The cases were generated using secondary sources of information (documents).

The selected case studies are:

1. A-10 Thunderbolt II (Warthog)

A close air support aircraft that was manufactured by Fairchild Republic, it was developed to provide close air support to the Army. (Jacques & Strouble, 2010).

2. C5 Galaxy

A large transport aircraft that was manufactured by Lockheed, it was developed to transport an Army division for long distance. (Griffin, C-5A Galaxy Systems Engineering Case Study, 2005).

3. B-2 Spirit

A stealth bomber that was manufactured by Northrop Grumman, it was developed to be a long range strategic bomber with stealth features. (Griffin & Kinnu, B-2 Systems Engineering Case Study, 2007).

3.5.3 Data Collection

The case study method is flexible and adaptable, and therefore single or multiple data collection methods can be employed to investigate the research problem (Cavaye, 1996). Various methods of data collection can be used, such as interviews, direct observation, participant observation, documentary sources, archival records and artefacts (Mouton, 2001; Myers, Qualitative research in business and management, 2009). Use of multiple data sources and multiple participants is preferred to triangulate data (Yin, 200). According to (Schultze & Avital, 2011), interviews do not automatically guarantee collecting of rich data and obtaining meaningful insights (Ponelis, 2015), and there is no single best method of data collection (Oyomno, 2013).

In this study, data was collected through secondary sources. Secondary data was collected using documentation and archival records. The secondary data sources were mainly published case studies of weapon systems development projects.

The qualitative method that was used to collect data was document analysis and observation.

3.5.3.1 Triangulation method

According to (Hussein, 2009), triangulation is a good research practice. There are four types of triangulation and these include data triangulation, investigator triangulation, theory triangulation and methodological triangulation (Hussein, 2009). Data triangulation refers to using numerous sources of data for the purpose of validation. For example, using two or more individuals as a source of data (Chaterera, 2013). Investigator triangulation involves using more than two investigators or researchers during any stage of the research study (Chaterera, 2013). It encompasses using several interviewers, observers or data analysts in the same study for the purpose of confirmation. Theoretical triangulation denotes to the use of numerous theories in one study, so as to support or contest the study findings because multiple theories enable the researcher to look at the problem with many lenses (Chaterera, 2013). Methodological triangulation involves applying many methods of investigation in one study (Chaterera, 2013).

The triangulation method employed in the study was data triangulation. Because document analysis was the only data collection method used in the study, it was imperative to triangulate the data for validation purposes. This involved using more than one source of data. Triangulation improves the evaluation of findings and validity of the research (Lund, 2005; Thurmond, 2001). (Thurmond, 2001) emphasised that triangulation plays a role in helping researchers understand the study matter, but does not improve a flawed study. When used appropriately, triangulation enhances the completeness and validation of data in the study research findings (Chaterera, 2013).

3.5.3.2 Document Analysis

The research study gathered data through document analysis. Document analysis is the systematic procedure of reviewing and evaluating documents, either printed or electronic (Bowen, 2009). Similar to other qualitative methods, it involves examining and interpreting data so as to obtain meaning, understating and develop empirical knowledge (Corbin & Strauss, 2008). Documents comprise text/ words and images recorded without the intervention of the researcher (Bowe, 2009). According to (Atkinson & Coffey, 1997), documents are 'social facts' that are produced, used and shared in socially organized ways

(Bowen, 2009). Documents can either be written or audio-visual, published or unpublished, public or secret, institutional or internal and current or retrospective (Ihlebaek, 2015). The documents used in this study were written published public documents.

The analysis procedure involved finding, selecting and synthesising the data contained in the documents for each case study. The data was organised into main themes, categories and case examples through content analysis (Labuschagne, 2003). During document analysis, the following context was taken into account; when and where the documents were made, by whom were the documents made, and who was the intended receiver of the documents (Ihlebaek, 2015). The document review was aimed at identifying systems engineering practices that occur during execution of defense acquisition projects.

Although document analysis has mostly been used to compliment other research methods, it can also be used as a stand-alone method (Bowen, 2009). For example, in a study by (Wild, McMahon, Darlington, Liu, & Culley, 2010) to investigate the information needs and document usage of engineers, the authors used the data to create new document use. Another study by (Gagel, 1997) carried out a comprehensive analysis of publications on technology and literacy. (Bowen, 2009) states that documents may be the necessary source of data for studies within the interpretive paradigm. Further, they are effective when events can no longer be observed or when details have been forgotten by informants (Bowen, 2009). Like any other data collection method, document analysis has both strengths and weaknesses. Strengths include: efficient method (less time consuming thus more efficient), availability (most documents are public), cost effectiveness (is less costly compared to other research methods), lack of obtrusiveness and reactivity (not affected by the research process), stability (presence of the researcher does not change whatever is being studied), exactness (inclusion of exact references, names and events details is useful), and coverage (offer broad coverage over time, events and settings) (Bowen, 2009; Merriam, 1988).

Weaknesses of document analysis include:

Insufficient detail. Documents are produced independent of a research agenda and commonly not detailed enough to answer the research question. To overcome this limitation, the researcher carried out an extensive review of the documents and selected only those that had sufficient detail for the study. Documents were selected for their completeness.

Low irretrievability. Documents may sometimes be irretrievable or difficult to retrieve as access may get blocked. The documents used in the study were published case studies thus fully accessible.

Biased selectivity. Indicated by incomplete collection of documents. For example, the documents available in an organisational context may probably align with the policies, procedures and the agenda of principals of the organisation. The researcher endeavoured to maintain objectivity when selecting the documents to use.

These weaknesses are mostly potential flaws than significant disadvantages, and the advantages of document analysis outweigh the limitations.

Content analysis of documents enabled the researcher to observe weakness or strengths in systems engineering that resulted in the success or failure of defense acquisition projects. Ultimately document analysis allowed the researcher to notice patterns and trends in systems engineering activities in weapon system development projects.

3.5.4 Data Analysis: Cross-case analysis

The qualitative data was analysed using cross-case analysis. The cross-case analysis technique deals with each individual case study as a separate study (Oyomno, 2013). Data was analysed using both vertical and horizontal analysis. Vertical analysis involved decreasing the material volume through summary (summarising and paraphrasing), while horizontal analysis involved comparing (related texts and themes to each other) (Vavrus & Bartlett, 2006).

The case study analysis was done by analysing and identifying similarities and differences across the cases so as to generate findings. The major steps of cross-case analysis were employed and these include: 1) data reduction, 2) data display, and 3) drawing conclusion and verification (Cruzes, Dybå, Runeson, & Höst, 2015)). The cross-case analysis method used in the study was Qualitative Comparative Analysis (QCA).

Although cross-case analysis was the major evaluation method used, within-case analysis was also carried out in the study. This was done through process tracing (or contribution analysis) to generate findings from individual cases. It facilitated identification of common systems engineering practices in the different case studies. The analysis involved assessing systems engineering activities in individual weapon systems development project cases and using the lessons learned to suggest recommendations.

3.6 Trustworthiness and Authenticity of the Research

In interpretivist research, the internal and external validity and reliability criteria of the positivist paradigm are replaced with the four widely acceptable criteria of authenticity and trustworthiness. These are credibility, dependability, confirmability, and transferability (Kivunja & Kuyini, 2017). Credibility refers to how well the data is authentic, believable and trustworthy (Kivunja & Kuyini, 2017). In the current study, this was ensured by carrying out an extensive check on the case studies selected and the documents used, to ensure that they were authentic and from reliable sources. All the case studies selected are documented by the Center of Systems Engineering at the Air Force Institute of Technology.

Dependability denotes the ability of observing the same outcomes under similar situations. Because it is improbable to reproduce the exact same results in interpretive research (Kivunja & Kuyini, 2017), the researcher ensured that the findings from the study truly emerged from the data collected and analysed. Dependability determines the quality of data collection and analysis (Kivunja & Kuyini, 2017), and is expressed by showing that the research systematically studied what it claimed to study (Miles & Huberman, 1994).

Confirmability is the degree to which the research findings can be confirmed by others, and aims to minimise biases (Kivunja & Kuyini, 2017). In this study, the researcher endeavoured to reduce personal biases by objectively reporting the findings, and all evidence was systematically reported so that the reader can confirm whether the findings flow from the data rather than the researcher's bias and subjectivity (Ponelis, 2015).

Transferability refers to the extent to which the study makes it possible for the reader to apply the findings of the investigated situation to other comparable situations (Bloomberg & Volpe, 2008). This was done by providing enough contextual data about the study such that readers can relate the study findings in their own context (Ponelis, 2015).

3.7 Ethical Considerations

Often, it is believed that using secondary data absolves researchers from the burdensome process of ethical approval application, or generally thinking about ethics (Tubaro, 2015). However, whether primary data is collected or not, ethical considerations should be taken into account in the research process. This starts right from the preliminary study design to communication of findings, which should ensure replicability, transparency and publicness.

Using secondary data in research is a highly ethical practice because it: maximizes the value of investment in data collection, lessens burden on respondents, ensures replicability of findings and hence more transparency of the procedures and integrity of the research (Tubaro, 2015). To fully realise the value of secondary data, the benefits should outweigh the risks of re-identification of individuals and revelation of sensitive information.

Therefore, in using secondary data, the following ethical conditions should be met:

- Before released to the researcher, data must be de-identified.
- Consent of study subjects can be reasonably presumed
- Outcomes of analysis must not permit re-identification of participants/ subjects.
- The use of data must not result in any damage or distress.

The aforementioned ethical issues were taken into consideration during the study.

3.8 Chapter Summary

This chapter explicitly discussed the research methodology of the study. It described and motivated the interpretivist paradigm, qualitative research approach and case study strategy adopted for the study. The chapter further presented the data collection and data analysis methods. Issues of trustworthiness and authenticity of the research were also addressed in this chapter. The chapter concluded by discussing the ethical considerations of the study.

4 CASE STUDY DESCRIPTION

4.1 Introduction

The purpose of this chapter is to briefly describe the case studies used in this study. Three case studies were used in the study. The case studies examined the systems engineering processes applied to three Department of Defense programs. The cases are the A-10 Thunderbolt II “Warthog”, the C-5A Galaxy, and the B-2 Spirit. The cases were selected based on willingness of the program experts to participate in the study, and they were all concerned with application of systems engineering in defense acquisition.

4.2 Case Study 1: A-10 Thunderbolt

This case study examines the SE process applied in the development of the A-10 Thunderbolt II. The A-10/OA-10 Thunderbolts IIs are extremely precise weaponry delivery aircraft, and can brilliantly manoeuvre at low altitudes and speed. They operate below 303.3 meters (1,000-foot) with a 2.4 kilometres (1.5 mile) visibility, and can loiter close to battle fields for prolonged periods of time. Although named the P-47 Thunderbolt, it is more generally known by its nickname ‘Warthog’ because of its uncommon appearance. The A-10 has a number of configurations which include; the first original A-10A, the A-10B, the two-seat model, the OA-10A, and the more recent A-10C (an upgrade of the A-10A). The A-10 has survived numerous early retirement and program cancellation attempts and is predicted to remain in operation until 2028, way beyond its initial requirement (Jacques & Strouble, 2010).

The main role

The major function of the A-10 aircraft is for Close Air Support (CAS) to the military. Other functions include forward air controller, combat rescue and search, interdictions, and special operations. The A-10/OA-10 Thunderbolt II allow for operations close to front lines due to their short take-off and landing ability, and wide-range combat radius. It has superior survivability compared other previous aircraft (Jacques & Strouble, 2010).

Manufacturer

The A-10A Thunderbolt II was manufactured between 1975 and 1984 by Fairchild Republic Corp. Other sub-contractors included General Electronic and Boeing (Jacques & Strouble, 2010).

Cost

The System Program Office estimated \$1.5 million (flyaway cost) whereas the contractor estimated \$1.4 million. However, procurement was based on CAIG's most feasible cost of \$1.7 million (with range of \$1.5 to \$2.0 million). The cost overruns of the program were projected at \$12 million (Jacques & Strouble, 2010).

Schedule

The development of the A-10 was approved on 28 February 1973. A-10A Thunderbolt II was manufactured between 1975 and 1984 by Fairchild Republic Corp. The A-10 development test and evaluation testing begun on 15 February 1975 and is projected to retire in 2028 (Jacques & Strouble, 2010)

4.3 Case Study 2: C-5A Galaxy

This case study explores the application of SE in the development of the USAF C-5A aircraft. The large transport/cargo aircraft was proposed to hastily stop advancing enemy when it became evident that the U.S would engage in conflicts from distant locations. The C-5 aircraft was the earliest of the behemoths and was the biggest aircraft in the world when it initially arrived into inventory in 1970, and is still the biggest transport cargo aircraft in the U.S military inventory. The C-5A fleet was successful in operation, but the aircraft development was faced with significant technical failure in the structure design, particularly the wing and pylon. The weakness resulted in restrictions in initial operations and necessitated designing and retrofitting a whole new wing to the original aircraft. The study examines the decisions taken (and those not taken), and the inadvertent consequences that resulted from the events (Griffin, C-5A Galaxy Systems Engineering Case Study, 2005).

The main role

The C-5A is a gigantic aircraft with ability to carry the heaviest Army M-60 tanks, bulky cargo (for instance the Chinook CH-47 helicopter), and other heavyweight army equipment for very long distances. The ramps (front and aft), enable ease of drive-on loading and drive-off unloading of military equipment and vehicles. The aircraft has carried a lot more cargo

consistently compared to any other aircraft during time of war, and still completes tasks that other military aircrafts cannot perform (Griffin, C-5A Galaxy Systems Engineering Case Study, 2005).

Manufacturer

The manufacture of the C-5A Spirit was spearheaded by the C-5 System Program Office and Lockheed, Georgia as the chief contractor (Griffin, C-5A Galaxy Systems Engineering Case Study, 2005).

Cost

The C-5A project was constrained by cost overruns right from the beginning throughout the program. While the Air Force estimated a total cost of \$1.86 billion, the contractor predicted \$1.71 billion (on September 4 1965). The actual cost by December 1965 had increased by an additional \$64 million. Although cost overruns were expected, the high final overrun of \$3.5 billion were not anticipated by anyone (Griffin, C-5A Galaxy Systems Engineering Case Study, 2005).

Schedule

The program begun in 1957. The C-5A first flight took place 33 months after the contract was awarded (on 28 June 1968). The last C-5A was delivered in 1973 (Griffin, C-5A Galaxy Systems Engineering Case Study, 2005)

4.4 Case Study 3: B-2 Spirit

The B-2 weaponry system comprises the B-2 aircraft and on board systems, facilities, training and support equipment and the personnel, encompassing all software and hardware. The B-2 Spirit case study captures systems engineering application during the design and development of the stealth bomber, USAF B-2 Spirit. The B-2 Spirit is a long-range heavy bomber and it represents a revolutionary advancement in technology and an ultimate shift in the modernization of the U.S bomber program. The case examines the SE process employed by the Air Force B-2 System Program Office, the major contractor, and the two sub-contractors from the start of the program to the first aircraft flight (Griffin & Kinnu, B-2 Systems Engineering Case Study, 2007).

The main role

The B-2 Spirit is a multi-purpose bomber with the ability to deliver both nuclear and conventional munitions. It delivers significant and accurate firepower in a short period of time,

through hitherto impenetrable defenses, anywhere in the world. The stealth characteristics (low observability) provide it with a distinct capability to penetrate the most advanced and sophisticated enemy defenses and threaten highly defended and valuable targets. It was mainly designed for strategic delivery of long-range nuclear, but considerable conventional capability was incorporated in the design from the start (Griffin & Kinnu, B-2 Systems Engineering Case Study, 2007).

Manufacturer

Several companies were responsible for designing and manufacturing the B-2 aircraft. Northrop Corporation was the major contractor responsible for the overall design and integration of the system. The others chief members of the contractor team were; Boeing Military Airplanes Co., Vought Aircraft Industries Inc., Hughes Radar Systems Group, and General Electric Aircraft Engine Group. The government agencies involved included the B-2 Program Office, Aeronautical Systems Division, and the Strategic Air Command (Griffin & Kinnu, B-2 Systems Engineering Case Study, 2007).

Cost

The contract cost was \$9.4 billion, awarded to Northrop on 17 October 1981. The target cost of the program was projected to be exceeded by \$2.3 - 2.9 billion (Griffin & Kinnu, B-2 Systems Engineering Case Study, 2007).

Schedule

The program contractors initially proposed a schedule of 48 months from go-ahead to first flight. However, after consideration, a schedule of 72 months was approved, with a risk mitigation and reduction period of two years. The program begun in late 1970s. The contract was awarded in December 1981 and the first aircraft flight was on July 17 1989 (Griffin & Kinnu, B-2 Systems Engineering Case Study, 2007).

4.5 Summary

This chapter described the three case studies used in this study. A brief description of each case study was given including the weapon system main role, its manufacturer, its cost and schedule. Finally, the analysis of the case studies were presented in this chapter.

The development of the assessment tool process will be discussed in the next chapter.

5 DEVELOPMENT OF THE ASSESSMENT TOOL

5.1 Introduction

This chapter outlines the development of the assessment tool that was developed as an assistance tool to improve systems engineering performance within defense acquisition projects. This chapter also presents the purpose of the proposed assessment tool, and discusses the content of the assessment tool.

5.2 Purpose of the Assessment Tool

The case study analysis provided an understanding of the research problem, for which an appropriate assessment tool could be useful. The expectation of the researcher is that if the assessment tool is properly applied, it will assist the efforts of improving systems engineering practices within defense acquisition projects. The proposed assessment tool can be used as an assistance tool along with any systems engineering procedures and tools.

5.3 Assessment Tool Development Process

The development of the assessment tool was guided by the results of the case study analysis of the three case studies that were used in this research study. Table 1 shows the contribution of each finding in the case study analysis to the assessment tool.

A. Pre-Materiel Development Phase	A10 Thunderbolt II*	R/Q	C5-A Galaxy**	R/Q	B-2 Spirit***	R/Q
Understanding of the Operational Capability Gap	The Air Force (AF) needed a close air support fighter that can be used in these three missions (1) Close Support Fire. (2) Armed Escort. (3) Armed Reconnaissance. The cost of the fighter had to be low.	A-4	The Air Force and the Military Air Transport Service needed a very large cargo aircraft that can transport an entire Army division for long distances.	A-4	The Air Force needed a long-range strategic bomber employing low observables (LO) or stealth features.	A-4
Requirements	Weight and performance capabilities: (1) Gross weight: Desired 22,500 lbs., Required 30,000 lbs. (2) Payload: Desired 8,000 lbs., Required 6,000 lbs. (3) Combat radius: Required 200 nautical miles. (4) Loiter time: Required 2 hours. (5) Minimum maneuvering speed at 500 ft.: Required 150 knots. (6) Turn radius at combat weight: Desired 1,000 ft., Required 2,000 ft. (7) Max speed at sea level with explosives: Desired 550 Knots, Required 450 Knots	B-1	Weight and performance capabilities: (1) Design weight: 764,000 lbs. at 2.25 g, 840,000 lbs. with the new wing, 920,000 lbs. in flight limit after refueling. (2) Maximum payload: 265,000 lbs. (3) Maximum fuel: 335,000 lbs. (4) Maximum landing weight 635,850 lbs. (5) Cruise performance: 440 knots at 30,000 feet. (6) Airport performance takeoff: 8,000 feet at maximum gross weight. (7) Airport performance landing: 4,000 feet with 100,000 lbs. cargo.	B-1	Weight and performance capabilities: (1) Length: 69 feet. (2) Height: 17 feet. (3) Wingspan: 172 feet. (4) Power plant: 4 GE F-118 engines. (5) Crew: Two pilots. (6) Max takeoff weight: 336,500 pounds. (7) Max in-flight weight: 357,500 pounds. (8) Max landing Weight: 311,500 Pounds. (9) Max payload: 44,000 pounds. (10) Max fuel: 166,900 pounds. (11) Min flying weight: 161,385 pounds. (12) Weight empty: 149,900 pounds. (13) Cruise performance 6,000 NM. (14) Takeoff, at sea level 8,000 feet at maximum takeoff weight. (15) Landing, 240,000 Pounds. weight: 5,000	B-1

					feet.	
	Low cost and achievement of weapon system effectiveness were two critical objectives of the project. The cost goal was \$1.4M per unit, for 600 aircraft	B-12	The aerospace industry helped in the assessment of: (1) The conceptual designs. (2) The technology readiness level	C-2	At the beginning of the program, the government and industry cooperated in: (1) Deriving, balancing, approving and documenting the aircraft requirements. (2) The early studies. (3) Preparation of the Request for Proposal (RFP). (4) The full-scale engineering development (FSED) proposal response by Northrop and Lockheed. (5) The source selection process. (6) Contract negotiation.	A-1, A-2, C-2

	Four key characteristics for the proposed design of the A-10: (1) Responsiveness. (2) Lethality (3) Survivability. (4) Simplicity	A-6	The definition of requirements for the aircraft involved all the necessary participant parties and their inputs were integrated.	A-8, A-9, B-4	The contract between the government and Northrop contained all the specifications developed at the time of source selection. The radar cross section (RCS) specifications however were not sufficiently mature. Therefore, the RCS model needed to be updated and tested.	C-1, C-2
	At the beginning of the project, the number and type of the engines were not set. The plan was to make the decision after conducting trade-space analysis considering cost, performance, maintainability and survivability.	B-1, B-2, B-3	Lockheed employed a state-of-the-art process in developing the operational analysis.	C-4, C-5, C-6	A specification addendum for the RCS was developed by the contractor and AF.	A-2, B-1, B-2
	The Air Force Armament Laboratory provided the necessary data and knowledge base for the weapons and delivery conditions for the aircraft.	A-5	The project team developed the lower level functional requirements from the top-level functional goal "moving an Army division to a distant location".	B-1	Engineering parameters of the aircraft were traded off sufficiently as independent variables.	B-3
	The close air support mission analysis identified four key characteristics: (1) responsiveness, (2) lethality, (3) survivability, and (4) simplicity.	A-5				B-3

	Responsiveness was defined as (1) the aircraft's ability to operate from bases very close to the area of operation, usually overseas bases. (2) The loiter time in the operation areas.	A-5, B-1				
	Responsiveness was also determined by the aircraft's ability to interface with the (1) Army. (2) Airforce (3) communication and control equipment	A-5, B-1				
	Lethality was defined as the aircraft's ability to carry (1) multiple types of bombs, guided missiles and rockets. (2) a new large caliber gun.	A-5, B-1				
	Survivability was defined as the aircraft's ability to be protected from (1) small arms. (2) anti-aircraft artillery. (3) Surface-to-Air missiles.	A-5, B-1				
	Survivability depends on several factors: (1) Maneuverability. (2) Redundancy (3) Shielding the crucial parts. (4) Shielding of Infrared Radiation (IR) (5) The size of the aircraft would be small. (5) The weapon delivery system design that would make the aircraft flexible in approaching and delivering of weapons.	A-5, B-1				

	Simplicity was defined as the aircraft's ability to: (1) Be developed in a short period of time. (2) Have a low life-cycle cost. (3) Have a less maintenance time. (4) Have high sortie rates. (5) operate from undeveloped forward bases.	A-5, B-1				
	The aircraft was planned to: (1) Be single manned. (2) Be lightweight. (3) Have sufficient range. (3) Have the ability to carry a great amount of a payload at low altitude with a significant loiter time. (4) Have the ability to maneuver when flying at low speeds. (5) Have the ability to be stable throughout a weapon release speed.	A-5, B-1				
	It was agreed on developing fixed mounted guns that are better than M-39 guns (20mm). A semiautomatic rifle (large caliber) was considered as well.					
	At least six weapon systems that have the capability of delivering all kinds of conventional ordnance.					
	A limited air-to-air missile were taken into consideration.					

	Survivability: The system design structure would have to: (1) Have a sealing fuel tank. (2) Have a backup system (manual). (3) Be able to protect the pilot and the aircraft's critical parts from anti-aircraft projectiles.	B-1				
	Maintainability: The aircraft was planned to be needing minimum maintenance.	B-1				
	The aircraft would be using existing newly developed equipment for avionics. (weapon system, navigation and communication)	B-1				
	The aircraft's communication equipment would have to be compatible with all other military forces (Army, Air Force, etc.)	B-1				
	The aircraft's navigation equipment would be required to: (1) Have the capability to navigate at night and in adverse weather conditions. (2) Have a maximum range to operate in far distant locations.	B-1				
	A depressible-reticle fixed optical sight is needed to be included in the design.	B-1				
	It was desirable to have a slant-ranging device if it had no effect on cost, reliability and cost.	B-1, B-3				

Mission Analysis	The mission analysis for the design included the following: (1) Warming-up and taking-off for five minutes. (2) climbing to 5000 ft. high. (3) cruising to 200 NM at 250 knots speed. (4) loitering for two hours. (5) descanting to sea level for 15 minutes of engaging in combat at 250-300 knots. (6) climbing to 5000 ft. (7) cruising back to the base at 5000 ft. high and 250 knots speed. (8) descanting and landing with reserve fuel for 20 minutes loitering time.	A-5	The mission analysis studies included: (1) Range. (2) Payload. (3) Speed. (4) Airport conditions at takeoff and landing.		The radar signatures requirements development process involved specialists from the company and government.	B-4
	The mission analysis resulted in using seven MK117 bombs and 1000 rounds of ammunition.	A-5	The mission analysis process involved inputs from (1) The contractors. (2) The development planners. (3) The user. (4) The technologist. (5) Experts from the cargo transportation community.	A-5	Mission Selected for Study: (1) Low Altitude Subsonic. (a) Survivability by low RCS, operating in clutter and terrain masking (b) Minimum positive elevation RCS to defeat look-down threats. (2) High Altitude Subsonic. (a) Survivability by low RCS, operating above threat detection range. (b) Minimum negative elevation RCS to defeat ground-based threats. (3) High Altitude Supersonic. (a) Survivability by low RCS, operating above threat detection range. (b) Survivability enhanced by	A-5

					speed. (c) Non-afterburning supersonic cruise.	
	The target types for the new gun were: (1) Infantry in foxholes. (2) Tanks and armored troops transport vehicles. (3) Hard targets (bunkers, ...etc.)	A-5	The team studied the feasibility of a very large aircraft as part of the early operational studies. The purpose of these studies was to determine the required technology to design and develop the aircraft.	C-2, C-3	Mission Analysis) Mission parameters of the aircraft included range, penetration altitude and elements of survivability, such as time in track, detection range, ...etc.	A-5
			The Army made a list of the vehicles and equipment to be carried by the aircraft.	A-5		

Planning/Executing the technical work	It was required of the winning contractor to deliver the first 18 aircraft to operational inventory before starting mass production. This was considered high risk in terms of cost and schedule. However, it was proposed to reduce the concept definition phase to four months to mitigate the risk.	B-6, B-7, B-8, B9	All employees at Lockheed were involved in the systems engineering process on a daily basis.	A-11, B-5, C-7, D-5	The Engine SPO was established, and General Electric was selected to develop the engine.	
	To reduce the technical risk, it was proposed to have a competitive prototype which could result in a better selection. However, the cost of the Research, Development, Testing and Evaluation (RDTE) phase by \$38.9M	B-6, B-7, B-8, B9	A weekly meeting was held every Wednesday morning. The meeting was to discuss the design, schedule, cost, systems engineering and integration.	A-11, B-5, B-6, B-7, B-8, B-9, B-10, B-11, B-13 B-14, B-15, B-17, C-7, D-5	The Weapon Systems Engineering (WSE) organization was established. The purpose of this organization is to be responsible for: (1) The evaluation process of the mission effectiveness of the weapon system. (2) The survivability of the weapon system. (3) The vulnerability of the weapon system. (4) All Low Observable (LO) technology development and evaluations. (Technology Maturation)	
	The Orelikon 304K gun would be tested as it could be used as an alternative option in case the contractor responsible for developing the gun failed.	B-6, B-7, B-8, B9	The program manager was involved in the systems engineering process. He was also involved in the tracking of the technical performance of the project.	A-11, B-5, C-7, D-5	In order to reduce the fabrication and manufacturing risks of some composite parts, the Air Force Research Laboratory's Manufacturing Technology Division efforts were incorporated into the B-2 program.	B-6, B-7, B-8, B-9, C-3

	The estimated cost is estimated to be from \$1M to \$1.2M. The cost of research and development is \$240M.	B-12, C-10, C-11	The SPO assigned the responsibility of identifying and mitigating risks to its engineers and Lockheed's manufacturing, logistics and other discipline staff.	B-6, B-7, B-8, B-9		
			The systems engineering process at the SPO and Lockheed were different. The SPO process focused on the requirements, while Lockheed's process focused on the design that meet the requirements.	A-11, B-5, C-7, D-5		
			The development of requirements process involved communication between all participating parties (systems management team, technical disciplines, designers, etc.).	B-4		
			The communication method used by the SPO, Lockheed and end user was outstanding.	A-11, B-5, C-7, D-5		

B. Materiel Solution Analysis	A10 Thunderbolt II*	R/Q	C5-A Galaxy**	R/Q	B-2 Spirit***	R/Q
Requirements	Translating the four key characteristics to performance requirements included lengthy trade studies.	B-1, B-3	During the evaluation of Lockheed's design proposal, the Air Force asked Lockheed to change their design as their current design would not meet the takeoff distance requirements. Lockheed agreed to change the design within four days.	B-2, A-7	The source selection evaluation board members were allowed to communicate directly with the Lockheed and Northrop's staff. This created a mutual understanding by both parties.	A-11, B-5, C-7, D-5
	One key metric of the aircraft's simplicity was the maintenance man hour per flying hours (MMH/FH).	B-1, B-2	The new design included increasing the empty weight by approximately 16,000 lbs. The new design included increasing the cost estimate by \$60M.	A-7	The requirements for infrared signature, radar cross section signature, acoustics, visual and emissions were new disciplines.	C-2
	Another aspect of simplicity was the aircraft's capability to be used from undeveloped bases.	B-1, B-2	The design was unable to meet the required fatigued life. This was a result of the Air Force insistence that Lockheed must meet the empty weight.	B-8, B-9, C-8, C-9, D-6, D-7		
	Maneuverability was considered to be a part of survivability. Maneuverability effects were analyzed against the aircraft loss probability.	B-1, B-2	The requirements development process included inputs from: (The end user. (2) Planners. (3) Developers. (4) Technologists from industry and government. This resulted in well understood requirements which were consistent during all phases.	B-4		
	Lethality studies involved weapon types, load-outs, the accuracy of tracking and	B-1, B-2				

	delivery.					
Planning/Executing the technical work	Historical data were analyzed to identify weaknesses of an aircraft. This resulted in four design features that must be taken into consideration: (1) Fuel tank must be protected from ground fire and not close to any ignition source. (2) Manual control should be invulnerable. (3) Crew compartment should be protected. (4) Engines should be protected and shielded.	C-3	All participating organizations were involved in the analysis of alternatives, communicating the updates to baseline to all other organizations.	A12, B-5, B-6, B-7, B-8, B-9, C-7,, C-8, C-9, D-5, D-6, D-7	The low observable trade space was analyzed by government and industry experts. The trade space included: (1) Low and high altitude. (2) Low subsonic to high subsonic speed. This resulted in the selection of a preliminary conceptual design that balances between the performance requirements and new technology.	C-5
			After trade studies, the team decided that one refueling is the most cost-effective option.	C-5	Many decisions related to the technical aspects of the aircraft and avionics subsystems were approached by a well-constructed architectural flow-down.	C-5
			In case of any disagreement regarding the design, Lockheed refers to the SPO for final resolution.	A-1	The communication between the Air Force technical and management staff and the contractor was outstanding.	A-11, B-5, C-7, D-5
			The SPO had a process of incorporating all inputs from non-SPO members via a specific configuration control board.	A-10, A-12, A-7	The Air Force SPO chief engineer and Northrop chief engineers had a one-day meeting every four to six weeks.	A-11, B-5, C-7, D-5

			The operational performance requirements and the design risks were successfully balanced during most of the project phases within the cost and schedule constraints.		These meeting were considered as great systems engineering tool. This was very similar to configuration control board.	A-11, B-5, C-7, D-5
			The Air Force's cost estimate was \$1.86B, While the Lockheed's estimate was \$1.71B. The actual cost of the development effort and the production of 115 aircrafts was \$3.5B.	B-12, C-10, D-8	Northrop's estimated the cost for the full-scale engineering and development of the aircraft at \$9.4B.	B-12, C-10, D-8
			The causes of the cost overrun were: (1) The original cost estimate by Lockheed was extremely low because they were expecting to use the design for commercial aircrafts. (2) The redesign of the original design within four days. (3) The low empty weight requirements. (4) The underestimation of the design and production effort.	C-11, D-9		
Contractor's Capability	The contractor at that time had not been running a full production line for 9 years.	B-18, B20	Lockheed made use of the configuration studies they had performed in the C-141. They found out that the T tail configuration was the best option to meet the requirements.	B-18, B20	Significant infrastructure expansion was required to perform the necessary work. All three contractors committed to invest more than \$2.5B in facilities, laboratories, equipment	B20, B-20

					and staff.	
	The Air force assessed Fairchild's capability, capacity and financial performance. The poor assessment of the company resulted in long term consequences which should have been noted during the assessment.	B20, B-20	It was very obvious that Lockheed's cost estimates were not realistic, but DoD and Air Force signed the contract.	B-12	Northrop and Lockheed were involved in the study contracts. They both used their conceptual design from their study. (Contractor's capability)	B19, B20
	The Air Force investigated Fairchild's facilities. The investigation concluded that the company might have the capability to perform the research, development, test and evaluation phases, but it's capability to perform the production was not efficient.	B20	Lockheed staff had developed two aircrafts together.	B-18		
C. Technology Maturation and Risk Reduction	A10 Thunderbolt II*	R/Q	C5-A Galaxy**	R/Q	B-2 Spirit***	R/Q
Requirements					The components of survivability included: (1) Takeoff distance (2) Reaction time. (3) System hardness. (4) observables. (5) Speed. (6) Altitude. (7) Active defense.	B-1, B-2

					The components of effectiveness included: (1) range. (2) Target acquisition. (3) Reliability. (4) Payload. (5) Bomb damage assessment. (6) Weapon accuracy. (7) Speed.	B-1, B-2
					Weight drove the aircraft range and high altitude capability requirements.	B-1, B-2
					The subsystem designs were approached by using the original requirements.	B-2
Planning/Executing the technical work	An unexpected problem occurred to the secondary gun gas ignition. This problem led to a flame area in the front part. This affected the vision of the pilot and led to variation in the pressure of the engine. To solve this problem, many approaches were suggested: (1) Making the barrel longer and using bonded ammunition made of plastic. (2) Adding a double-deflector. (3) Adding a potassium nitrate suppressant to the propellant. After applying these approaches and testing the gun, the problem was resolved.	B-6, B-7, B-8, B-9, B-17, C-8, C-9, D-6, D-7, D-11, D-15	The systems engineering processes were conducted on a daily basis which resulted in a strong relationship between the project staff.	A-11, B-5, C-7, D-5		

	Solving the above problem resulted in another one. The gun firing produces enormous amount of residue. The problem was solved by adding a windshield washer on the front of the gun canopy.	B-6, B-7, B-8, B-9, B-17, C-8, C-9, D-6, D-7, D-11, D-15	All ground testing was conducted before the flight test. This has a positive effect on the technical aspects of the design and production processes.	D-3	Six configuration item specifications were required to be developed in the contract. The specifications were: (1) Radar. (2) Avionics. (3) Armament. (4) Flight control. (5) Low observables. (6) Software.	A-6
	New manufacturing technologies were introduced in this project to reduce the risk and cost of the depleted uranium penetrator.	C-2	The systems engineering process included developing initiatives by the design and production teams to save weight in order to meet the required empty weight.	B-6, B-7, B-8, B-9, C-13, C-17, D-11, D-15	The basic architecture of the aircraft was derived during the study phase. The primary objectives of the design were: (1) Survivability. (2) Effectiveness. (3) Range/payload and lift/drag.	A-6
	The gun angle was found to be not suitable for low slant range strafing nor low dive angle. After conducting several tests, it was suggested that in order to solve this problem, the gun alignment should be changed by 2 degrees. This suggestion was applied and the problem was resolved.	C-3, C-13, C-17, D-4	The AF refused to make any design tradeoffs regarding the weight and performance.	A-11, B-5, B-6, B-7, B-8, B-9, C-7, C-8, C-9, D-5, D-6, D-7	The radar resolution specifications were traded off especially in the areas of: (1) High navigation accuracy. (2) Capability to acquire a wide range of target types. (3) Performing bomb damage assessment. (4) Ability to recognize patterns. (5) Capability to accurately deliver weapons.	B-2, B-3

	At the full-scale development phase, the armor piercing round was proved to be insufficient. Therefore, it was decided not to proceed with this approach.	D-4, D-11, D-15	The Army and Military Air Transport Service experience were used to predict the environment at the landing sites. The derived requirement of operating from undeveloped runways resulted in several new requirements such as: (1) The aircraft was required to operate on a surface with a California Bearing Ration of 92. (2) The aircraft was required to have a high flotation landing gear configuration. (3) The aircraft was required to be ready to operate at any time, that means it is required to operate in high crosswind (at 35 kts).. (4) The aircraft was required to have a crosswind gear capability. That means the landing gear bogies were required to glide into the wind.	A-5, A-6, A-8, A-9	The specification board meeting was attended by government staff only. While Northrop had an informal board meeting to discuss all the company's inquiries, modification requests and deficiency reports.	A-11, B-5, C-7, D-5
	A 26-month phase called The Competitive Prototype Phase took place. The main purpose of this phase is to select two contractors that will design, develop and build their prototype designs for flight test.	B-14, B-15, B-16, B-17, C-14, C-15, C-16, D-12, D-13, D-14	The Systems Engineering process applied by the government was responsible for tracking the design and how it meets the functional baseline. Lockheed on the other hand was required to show how the functional baseline was implemented in the	A-1, A-2, D-1, D-2	A modification request was mandatory for all specification changes.	A-3, A-10, A-12, A-7

			design.			
	A 33-month competitive prototype phase for the gun was recommended.	B-14, B-15, B-16, B-17, C-14, C-15, C-16, D-12, D-13, D-14	A new test facility was established to test the engine. It was staffed by GE as well as Lockheed employees.	B-19		
			The architecture tree of functional requirements was developed based on the top-level functional statement "moving an Army division to a distant location".	C-4, C-5, C-6		

D. Engineering and Manufacturing Development	A10 Thunderbolt II*	R/Q	C5-A Galaxy**	R/Q	B-2 Spirit***	R/Q
Requirements (Design)	Gun: GE design met all the performance requirements except the weight. There was a variation of 224lbs. Although, the design won and GE proceeded with the development of the gun.	D-1, D-2, D-3	The program manager of the C-5A had a meeting with the SPO to request a permission to change the engine thrust rating at sea level. The request was rejected.	A-3, A-10, A-12, A-7	The testing of the radar cross-section resulted in affecting the performance of the vane. An expert in inlet design was brought up to look at the challenge. The expert recommended to change the shape of the inlet so the vane is no longer needed. Testing the new design showed improved performance of the intel.	D-4
	The Northrop's design was a twin turbofan aircraft. The design was a high wing aircraft and the engines were adjacent to the fuselage and under the wings. The design required a larger wing span to meet the take-off distance and low-speed maneuvering requirements.	D-1, D-2, D-3	Lockheed requested SPO to increase the required empty weight by 14,000 lbs. The request was rejected.	A-3, A-10, A-12, A-7	A study to include low penetration altitude capability was requested through a modification request. The Air Force and Northrop formed a team to study the tradeoffs between: (1) Low altitude penetration altitude and speed. (2) survivability. (3) Impact on range and cruise performance. This resulted in a modification to the baseline design.	A-3, A-10, A-12, A-7

	Northrop's design has survivability features such as self-sealing fuel tank, hydraulic flight controls, back-up flight controls, access doors that can blow out when an explosion occur and armor plating to protect the cockpit.	D-1, D-2, D-3	A new weight allocation was approved. The wing group received 3,750 lbs. increase.	A-3, A-10, A-12, A-7	Adding an isolation panel was one of the changes recommended to Northrop configuration baseline. The main purpose of this isolation panel is to escalate the instrument panel and ejection seats. After conducting systems engineering studies, it was believed that this change will negatively affect the crew's performance, so it was rejected.	A-3, A-10, A-12, A-7
	Northrop's design has 30 minutes engine replacement time as a maintenance feature.	D-1, D-2, D-3	To meet the required 30,000-hour service life, the net weight of the aircraft had to increase by 14,641 lbs.	A-3, A-10, A-12, A-7	Several alternatives were examined to optimize the capability of low altitude penetration. Modifying the high-altitude design to be able to perform the low altitude missions was the most cost-effective option.	A-3, A-10, A-12, A-7
	The Fairchild's design was also a twin engine turbofan aircraft. The engines were located behind and above the wing.	D-1, D-2, D-3				A-3, A-10, A-12, A-7

	The Fairchild's design has a survivability features such as titanium armor around the cockpit, hydraulic flight controls, mechanical back-up flight controls, self-sealing fuel tank, vertical stabilizers and landing gears that make landing safer.	D-1, D-2, D-3				A-3, A-10, A-12, A-7
	The flight tests of the two aircrafts took place to select the best one. The purpose of the test was to test the performance of the aircrafts in difficult flying conditions.	D-2				
	The weapon system accuracy which was not a that important at that stage was tested. The two designs results were very similar with only minor differences.	D-2				
	The Fairchild's design outperformed the Northrop's design in the ground handling capability. This can be attributed to the low wing design and the capacity to have more ordinance. The Fairchild's design was closer to be manufactured.	D-2				
	The simplicity of the Fairchild's design made it more attractive to achieve the cost of \$1.4M per unit.	D-2				

	Pilots were asked to fly the two aircrafts, they preferred the Fairchild's aircraft for combat operations.	D-2				
	After the flight tests of the two aircrafts, the two guns developed by GE and Philco Ford were tested.	D-1, D-2, D-3				
	A task to estimate the cost of the remaining of the program was authorized. The Defense Systems Acquisition Review Council (DSARC) estimated the cost of \$1.7M per unit with an uncertainty range of \$1.5M to \$2.0M. The SPO estimated the cost of \$1.5M per unit. The contractor estimated the cost of \$1.4M per unit. The DSARS recommended a cost of \$1.5M per unit.	B-10, B-11, B-12, B13, C-10, C-11, C-12, D-8, D-9, D-10				
	The DoD approved a full-scale development of the Fairchild's design on a cost of \$1.7M per unit. The Air Force awarded a contract for about \$160.0M. GE was awarded a contract for about \$28.0M to develop the engines.	B-10, B-11, B-12, B13, C-10, C-11, C-12, D-8, D-9, D-10				

	GE was also awarded a contract for about \$24.0M for delivering seven pre-production guns and refurbish the prototype guns. GE was also ordered to develop a family of 30 mm ammunition.	B-10, B-11, B-12, B13, C-10, C-11, C-12, D-8, D-9, D-10				
Planning/Executing the technical work	Ground firing of the refurbished prototype guns as well as the second gun resulted in no major problems.	D-2	Extensive laboratory testing was required for the development tests. New tests were built up for the qualifications of this aircraft.		In their response to the contract, Northrop proposed fabrication and manufacturing risk reduction studies and development tools, equipment and facilities to mature the technology of composite materials which are going to be used in the program. The proposed concept was to use the existing Air Force Materials Laboratory effort to mitigate the risks.	C-2, C-3
	\$12.0M overrun and schedule problems were reported. Some key components were received late by some vendors.	A-13, A-14, A-15, A-16, B-10, B-11, B-12, B-13, B-14, B-15, B-16, B-17	The wing structure and pylon were replaced because of the fatigue cracks.		The aero-elastic instability of the aircraft structure was another challenge to be resolved. The aircraft planform needed to be modified, this means the original configuration baseline was updated.	A-3, A-10, A-12, A-7

	The SPO, Air Force contract management division and air force plant representative office had lack of coordination. This was believed to have an impact on Fairchild's responsiveness.	A-11, B-5, C-7, D5	Serious problems were obvious during building the aircraft concerning the fatigue life and the wing static test.		The analysis of the aircraft control system showed that the control power to reach the gust load alleviation requirements was insufficient. In order to resolve this challenge, the trailing edge was modified and the original baseline was updated.	A-3, A-10, A-12, A-7
	The Air force was authorized to proceed with an initial production of 52 aircrafts using \$39.0M.	A-13, A-14, B-10, B-11, B-12, B-13	The independent review team assessed the structure of the aircraft to ensure flight safety. Several restrictions were suggested. A new wing was designed to resolve the problem.		The design team was asked to examine alternatives for improved load balancing. The team recommended that the structure baseline must be changed.	A-3, A-10, A-12, A-7
	The qualification tests for the engine were completed	D-1, D-2, D-3				A-3, A-10, A-12, A-7
	Several tests were required for the purpose of proceeding with full rate production including: (1) Freedom from flutter (2) Initial performance measurements (3) Flying qualities (4) Gun accuracy (5) Ammunition performance (6) Bombing accuracy (7) Laser spot seeker integration (8) Aerial refueling (9) Initial operation test and evaluation.	D-1, D-2, D-3				

	Fatigue testing was conducted, the aircrafts developed cracks on the fuselage frame at about 80% of its intended lifetime. The problem was resolved by applying reinforcements to the aircraft.	B-6, B-7, B-8, B-9, B-17, C-8, C-9, D-6, D-7, D-11, D-15				
	A full production was authorized at a maximum rate of 15 aircraft per month. This was less than the predicted rate of 20 aircraft per month, such a reduction was a result of the poor assessment of the contractor's financial and technical capabilities.	B-19, B-20				

Table 1: Case study analysis and Contribution to the assessment tool

* (Jacques & Strouble, 2010)

** (Griffin, C-5A Galaxy Systems Engineering Case Study, 2005)

*** (Griffin & Kinnu, B-2 Systems Engineering Case Study, 2007)

5.4 Discussion of the Assessment Tool

The assessment tool was developed based on the findings of the case study analysis that were presented in previous chapter. The focus of the assessment tool is on the following:

1. Developing well-constructed requirements from the beginning of the project.

This can be achieved by:

- Understanding the operational capability gap.
 - Defining the design mission (mission analysis).
 - Identifying the owner and developer of the requirements.
 - Identifying all participating parties that affect or are affected by the project. For example, government, contractors, subcontractors, end user, ...etc.
 - Including all the parties that affect or are affected by the requirements in the process of developing the requirements.
 - Ensuring the requirements are well defined.
 - Establishing a process for funding new specifications that are not part of the original contract.
 - Frequently assessing the sufficiency of the process of developing the requirements.
 - Ensuring sufficient trade-off analysis during the development of the requirements.
2. Tracking any change(s)/modification(s) to requirements and assessing its/their effect on performance, cost and schedule.
 3. Assessing the contractor's capability to perform the required work before signing the contract.
 4. Ensuring smooth communication between all parties regarding:
 - Day-to-day work.
 - The development of the requirements.
 - Solving any expected or unexpected challenges/problems/risks/hazards.

5. Studying and testing any new technology (if existed), and assessing whether applying the new technology has any impact on requirements, cost and schedule.
6. Identifying all people/organisations that affect or are affected by the cost and schedule, and incorporating their inputs in cost and schedule planning.
7. Assessing the effect of any changes of the requirements to the cost and schedule and update them accordingly.
8. Assessing the effect of any expected or unexpected challenges/problems/risks/hazards to the cost and schedule and update them accordingly.
9. Tracking the cost and schedule frequently.
10. Establishing a process of defining the operational and system architecture, making sure to involve proper trade analysis in the process, and assessing its sufficiency along the way.
11. Establishing a product/system baseline and verifying it against the requirements.
12. Making sure that the product/system is producible.
13. Assessing the effect of any changes to the requirements, cost and schedule that may result from building the product/system.

Table 2 presents the assessment tool that was developed for this study.

#	A. Pre-Materiel Development Phase	Yes	Partially	No	N/A	Action
	Requirements					
A-1	Is the owner of the requirements identified?					
A-2	Is the developer of the requirements identified?					
A-3	Is the person/organization that is responsible for approving the requirements/requirements change identified?					
A-4	Is the operational capability gap fully understood?					
A-5	Is the design/operational mission clearly defined?					
A-6	Are the top-level requirements clearly defined?					
A-7	Is the process of assessing requirements change to performance involved trade-offs against cost, schedule and risk established?					
	Communication/Integration					
A-8	Are all participating parties of the project identified?					
A-9	Is the process of incorporating all inputs for developing the requirements from all participating parties established?					
A-10	Is the process of handling requirement change/modification clear to participating parties?					
A-11	Is the process of sharing information regarding day-to-day work established?					
	Cost					
A-12	Is the process of funding new specifications that are not part of the original contract clearly established?					
A-13	Are all the people/organizations that affect/are affected by the cost of the Materiel Solution Analysis phase identified?					

A-14	Is the process of incorporating all the people/organizations that affect/are affected by the cost of the Materiel Solution Analysis phase established?					
	Schedule					
A-15	Are all the people/organizations that affect/are affected by the schedule of the Materiel Solution Analysis phase identified?					
A-16	Is the process of incorporating the inputs of all people/organizations that affect/are affected by the schedule of the Materiel Solution Analysis phase established?					
	B. Materiel Solution Analysis	Yes	Partially	No	N/A	Action
	Requirements					
B-1	Are all the requirements (up to the lowest level) clearly developed?					
B-2	Is the process of developing the requirements (up to the lowest level) sufficient?					
B-3	Does the process of developing the requirements involve proper analysis of alternatives against cost, schedule and performance?					
B-4	Is the process of incorporating all inputs for developing the requirements from participating parties sufficient?					
	Communication/Integration					
B-5	Is the process of sharing information regarding day-to-day work sufficient?					
B-6	Is the process of incorporating all inputs for expected/unexpected challenges/problems/risks/hazards from participating parties established?					
B-7	Is the process of incorporating all inputs for expected/unexpected challenges/problems/risks/hazards from participating parties sufficient?					
B-8	Is the process of dealing with expected/unexpected challenges/problems/risks/hazards established?					
B-9	Is the process of handling expected/unexpected challenges/problems/risks/hazards sufficient?					
	Cost					

B-10	Are all the people/organizations that affect/are affected by the cost of the project identified?					
B-11	Is the process of incorporating inputs from all the people/organizations that affect/are affected by the cost of the project established?					
B-12	Is the cost estimate for the project sufficient?					
B-13	Is the process of incorporating inputs from all the people/organizations that affect/affected by the cost of the project sufficient?					
	Schedule					
B-14	Are all the people/organizations that affect/are affected by the schedule of the project identified?					
B-15	Is the process of incorporating inputs from all people/organizations that affect/are affected by the schedule of the project established?					
B-16	Is the schedule estimate of the project sufficient?					
B-17	Is the process of incorporating inputs from all people/organizations that affect/are affected by the schedule of the project sufficient?					
	Contractor's Capability					
B-18	Does the contractor have any experience in projects similar to the current project?					
B-19	Does the contractor have the needed technical capability to perform the required work?					
B-20	Does the contractor have the needed financial capability to perform the required work?					
	C. Technology Maturation and Risk Reduction	Yes	Partially	No	N/A	Action
	Requirements					
C-1	Are all the requirements clearly understood?					
C-2	Are all new technologies that are involved in the project properly studied and tested/verified?					
C-3	Does the process of maturing the technology not result in any change/modification to the initial requirements?					
C-4	Is the process of defining the operational and system architecture established?					

C-5	Does the process of defining the operational and system architecture involve proper Analysis of Alternatives (AoA)?					
C-6	Is the process of defining the operational and the system architecture sufficient?					
	Communication/Integration					
C-7	Is the process of sharing information regarding day-to-day work sufficient?					
C-8	Is the process of incorporating all inputs for expected/unexpected challenges/problems/risks/hazards from participating parties sufficient?					
C-9	Is the process of dealing with expected/unexpected challenges/problems/risks/hazards sufficient?					
	Cost					
C-10	Is the cost estimate for the project sufficient?					
C-11	Is the cost tracked frequently and changes to the baseline are reflected in the cost estimates?					
C-12	Is the process of incorporating all the people/organizations that affect/are affected by the cost of the project sufficient?					
C-13	Does the process of maturing the technologies not result in any changes/unforeseen challenges that might affect the cost of the project?					
	Schedule					
C-14	Is the schedule estimate of the project sufficient?					
C-15	Is the schedule tracked frequently and changes to the baseline are reflected in the project schedule?					
C-16	Is the process of incorporating inputs from all people/organizations that affect/are affected by the schedule of the project sufficient?					
C-17	Does the process of maturing the technologies not result in any changes/unforeseen challenges that might affect the schedule of the project?					

	D. Engineering and Manufacturing Development	Yes	Partially	No	N/A	Action
	Requirements					
D-1	Is the initial product/system baseline established?					
D-2	Is the initial system/product baseline verified against the requirements?					
D-3	Is the initial system/product baseline producible?					
D-4	Does the process of building the product/system or verification not result in any changes to the product/system baseline?					
	Communication/Integration					
D-5	Is the process of sharing information regarding day-to-day work sufficient?					
D-6	Is the process of incorporating all inputs for expected/unexpected challenges/problems/risks/hazards from participating parties sufficient?					
D-7	Is the process of dealing with expected/unexpected challenges/problems/risks/hazards sufficient?					
	Cost					
D-8	Is the cost estimate for the project sufficient?					
D-9	Is the cost tracked frequently and changes to the baseline are reflected in the cost estimates?					
D-10	Is the process of incorporating all the people/organizations that affect/affected by the cost of the project sufficient?					
D-11	Does the process of building/verifying the system/product not result in any changes/unforeseen challenges that might affect the cost of the project?					
	Schedule					
D-12	Is the schedule estimate of the project sufficient?					
D-13	Is the schedule tracked frequently and changes to the baseline are reflected in the project schedule?					
D-14	Is the process of incorporating inputs from all people/organizations that affect/are affected by the schedule of the project sufficient?					

D-15	Is the process of building/verifying the system/product not resulted in any changes/unforeseen challenges that might affect the schedule of the project?					
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Table 2: The Assessment Tool

5.4.1 Questions of the Assessment Tool

The assessment tool consists of 68 questions divided into four phases; pre-materiel development decision, materiel solution analysis, technology maturation and risk reduction, and engineering and manufacturing development. The questions are grouped into five categories; requirements, communication and integration, cost, schedule and contractor's capability.

5.4.2 Answers of the Assessment Tool

The questions of the assessment tool have four possible answers and these are: "Yes", "Partially", "No" and "Not Applicable (N/A)". The implication of each answer is presented below.

1. Yes

If the answer to the question is "yes", this implies that the project is performing well. **No action is needed.** The optimum situation of the project is if all questions are answered "Yes".

2. Partially

If the answer to the question is "partially", this implies that the project is not performing up to the expected level. In this case, **an action is advisable** to correct the situation.

3. No

If the answer to the question is "no", this implies that there is a problem that needs to be solved. In this case, **an action must be taken** in order to solve the problem.

4. N/A

If the answer to the question is "N/A", it means that the question is not applicable to the project and **no action is needed.**

Action

If the answer to the question is either "partially" or "no", an action should be written under the Action column. For example, if Question A-2 (**Is the developer of the requirements identified?**) is answered "No", an action could be "Identify the requirements developer". The recommended Actions suggested can then be implemented (as applicable) during execution of the project to improve performance and project outcome.

5.5 Summary

This chapter presented an assessment tool that can be used to improve systems engineering performance in defense acquisition projects, which can help solve the problems of cost overruns and schedule delays that these projects are normally faced with. The purpose of the assessment tool was presented in this chapter. Furthermore, the assessment tool development process was discussed in this chapter. Finally, the content of the assessment tool was discussed at the end of this chapter.

6 EVALUATION OF THE ASSESSMENT TOOL

6.1 Introduction

One of the main steps in this study was to evaluate the assessment tool. This is because it offers important feedback on the improvement of the assessment tool developed. This chapter provides the details of the evaluation process that was conducted for the purpose of this research.

6.2 Method of Evaluation

In this research study, the developed assessment tool was evaluated using Subject Matter Expert reviews. Review of a subject by experts is the main validation method in fields such as systems development, software development, simulation and modelling (Pace & Sheehan, 2002). This method is extensively used because it offers insight about a subject or topic, and also provides real world information or data which are usually unavailable to permit robust quantitative validation. Expert reviews are also known as 'peer reviews' and the experts referred to as 'subject matter experts'. Subject Matter Expert reviews are commonly used in areas with limited documented guidelines in systems engineering, simulation and modelling, and software communities, which do not have formal standards for these reviews (Pace & Sheehan, 2002). This evaluation method was therefore appropriate for this research study.

6.3 Analysis and Discussion of the Evaluation Results

The evaluation was conducted by experts whose area of expertise fall within the defense industry, specifically product development. The evaluation was conducted virtually through emails that were sent to the experts. Out of the three experts that were contacted, two experts participated in the process of evaluating the assessment tool.

The feedback received from the experts were grouped into the following categories:

6.3.1 Relevancy of the Assessment Tool to Systems Engineering

Both experts agreed that the content of the assessment tool is relative to systems engineering. However, Expert 1 mentioned that there are two approaches in requirement development. The

first approach is when the end user funds the project and conducts supervision of the requirements development.

The second approach is when the manufacturer develops the requirements and funds the project. The project could be supported by other parties such as the government or end user. According to him, this approach is more widely used within the defense industry. However, this research is based on projects that used the first approach.

Expert 2 argued that some questions on the assessment tool regarding schedule and cost leaned over to project management. However, the questions regarding baseline, verification and requirements and their influence on cost and schedule are relevant to systems engineering.

6.3.2 Advantages of the Assessment Tool on the Defense Industry

The experts were asked about the advantages that the developed assessment tool would have if applied on real defense acquisition projects. Expert 2 thinks the assessment tool could be used as a checklist to identify important aspects of the project that would otherwise be neglected. Contrary, Expert 1 does not think that the assessment tool would have a big effect on the defense industry. He pointed that in the defense industry only few projects are funded by the end user.

6.3.3 Downsides of the Assessment Tool

The experts were asked about the downsides of the assessment tool. Expert 1 believes that one of the biggest challenges of a defense acquisition project is the technical interface management. He suggested that the aspect of technical interface management be added to the assessment tool. Expert 2 however challenges the practicality of the assessment tool as it might be quite lengthy to be completed. He said that it might be difficult to be completed within a large group of people on a regular bases.

6.3.4 Shortfalls of the Assessment Tool

Based on the feedback from the experts, the assessment tool has several shortfalls. Both experts agree that the assessment tool does not address the interface management between subsystems. Additionally, Expert 1 thinks that the engineering and manufacturing development phase needs to be expanded to include process qualification as it could cause huge cost overruns and schedule delays.

Beside the interface management, Expert 2 suggested the following to be included in the assessment tool:

- Project Priorities (Safety, performance, cost etc.)
- Hazard management
- Availability of raw materials (lead times)
- Availability of resources (personnel, equipment)

Despite the shortfalls of the assessment tool, it can still be used as an assistance tool to improve systems engineering performance in defense acquisition projects because of its strength in identifying systems engineering areas with performance issues and also important aspects of a project that would otherwise be neglected. However, the developed tool can further be improved to take into consideration the issues/concerns that were raised by the Subject Matter Experts.

6.4 Summary

This chapter presented the evaluation of the proposed assessment tool. The method that was adopted for conducting the evaluation of the assessment tool was discussed. This chapter also presented the analysis and discussion of the evaluation results.

7 CONCLUSION

7.1 Introduction

This chapter presents the conclusions, contribution of the study, and research directions based on the findings of the study presented in chapter four and interpreted in chapter five. These were guided by the research aim, research questions, and the problem the study attempted to solve.

The main aim of this research study was to develop an assessment tool to improve the systems engineering activities during execution of any weapon systems development project. To achieve this, the study adopted an interpretive position, using the case study and document analysis research methods. This chapter presents the overview of the research study, presents the contribution of the study, future research directions and conclusion.

7.2 Overview of the Research Study

The purpose of developing an assessment tool is to ensure that the performance of systems engineering can be improved during execution of weapons systems projects to improve output of projects, save costs (reduce cost overruns) and meet schedule (avoid schedule delays). Prior works have developed assessment tools that can be implemented after a weapon systems project is complete. This study fills a gap by developing an assessment tool that can be implemented during execution of a weapon systems development project.

Chapter one: presented the background to the study. This included challenges of new product development in the defense sector and the relevance of systems engineering in defense acquisition. The relationship between systems engineering and program outcomes was covered, as well as the cost of poor implementation of systems engineering and the need for an assessment tool to improve the performance of systems engineering in defense acquisition projects. It covered the knowledge gap and thus in developing the assessment tool, the focus is on improving performance of systems engineering during execution of weapon systems development projects. Chapter One presented the structure of the thesis.

Chapter two: provided a detailed literature review on systems engineering and defense acquisition. It discussed the systems engineering lifecycle processes which included technical management processes and technical processes. The technical management processes

included technical planning, decision analysis, technical assessment, requirements management, risk management, configuration management, technical data management and interface management. Whereas the technical processes included stakeholder requirements definition, requirements analysis, architecture design, implementation, integration, verification, validation and transition.

The review also presented in detail the defense acquisition framework/lifecycle. The different phases and milestones of the lifecycle, the purpose and the documents involved in each phase and milestone were discussed. The phases comprised pre-materiel development decision phase, materiel solution analysis phase and milestone A, technology maturation and risk reduction phase and milestone B, engineering and manufacturing development phase and milestone C, production and deployment phase, and operations and support phase.

Understanding the application of systems engineering in defense acquisition is critical since it affects the project outcome. Thus the chapter also discussed the application of systems engineering in each of the phases of the defense acquisition framework and the systems engineering activities involved in each phase. The review uncovered the challenges facing defense acquisition projects particularly with reference to cost overrun and schedule delays. The causes of failure of defense acquisition projects were revealed, and past attempts at improving systems engineering performance in defense acquisition projects were also covered. The researcher identified the Friedman and Sage Framework as suitable for the research study.

Chapter three: outlined the research paradigm and underpinnings of the study. The research philosophy underpinned the study in the interpretivist paradigm. The research study followed a qualitative research approach. The qualitative approach enabled gaining a good understanding of the performance of systems engineering in the context of weapon systems development and also enabled the development of the assessment tool. The research methodology was also covered. Three case studies and document analysis were conducted.

Since the study aim was to develop an assessment tool for improving performance of systems engineering in defense acquisition projects, the case study method and document analysis were selected so as to obtain insight into the study. Three case studies were conducted in this research study. The cases were selected based on the systems development projects executed according to the DoD systems engineering model. The research approach, methodology and data collection techniques used in the study were provided in the chapter. The case studies were described in chapter four.

Chapter four: described the three case studies selected for this research study. The case studies evaluated the application of the systems engineering processes in three projects of the Department of Defense. The case studies included the A-10 Thunderbolt II “Warthog”, the C-5A Galaxy, and the B-2 Spirit. The chapter highlighted the description, main roles, manufacturer, cost and schedule of each of the cases.

Chapter five: interpreted the findings and analysis from the case studies, and this led to the development of the proposed assessment tool. The chapter presented the purpose of the assessment tool, the development process, discussion of the focus and content of the assessment tool.

Chapter six: presented the evaluation process of the assessment tool. Due to time considerations, a Subject Matter Review method was chosen as the evaluation method of the assessment tool. An evaluation form was distributed to three experts in the product development field within the defense industry. Two out of the three experts provided their feedback on the assessment tool. The feedback of the experts was presented in this chapter.

7.3 Research Contribution

The research study made a practical contribution and also contributed to the body of knowledge. The study developed a standardised framework for understanding the systems engineering performance issues that influence the outcomes of weapon systems development projects, and identifying focus areas for improvement of systems engineering performance.

Several studies have developed assessment tools that can be implemented after completion of a project. The present study focused on evaluation of systems engineering performance during execution of a project. Thus this research study filled a gap and contributed to the industry by developing an assessment tool that can be implemented during execution of weapon systems projects so as to improve the performance of systems engineering in defense acquisition projects. This provides a solution that can be implemented in the industry as a standard decision making tool.

The study also contributed to the body of knowledge by providing an understanding of the systems engineering and defense acquisition frameworks/lifecycles, and the challenges and factors that contribute to the success or failure of defense acquisition projects. This provides

projects with an understanding of the critical areas of focus during implementation of systems engineering in weapon systems development projects.

From evaluation of the case studies, the research study also contributed to the body of knowledge by identifying real-world challenges facing systems engineering application in weapon systems development projects, and proposed solutions to solve these challenges.

7.4 Future Research Directions

Future research should focus on improving the developed assessment to suit a specific type of weapon system for example land systems, air systems and navy systems among others.

The developed assessment tool can also be improved to fit a specific company or organization based on its practices in conducting systems engineering.

Evaluation of the developed assessment tool using quantitative methods can be explored in future studies, and repeated in diverse environments.

7.5 Conclusion

The aim of the study was achieved through four research objectives and the five research questions that were formulated. Poor implementation of systems engineering in defense projects affects the project outcomes. Therefore, the study developed an assessment tool for evaluation the performance of systems engineering during execution of weapon systems projects.. Furthermore, practical challenges facing systems engineering application in defense acquisition projects in the industry were identified, solutions proposed, and suggestions made for future research.

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