

https://dspace.org/

Systems engineering in the research and development environment

Ramdas, Ashlin

2017

https://hdl.handle.net/10539/26029

Ramdas, Ashlin (2017) Systems engineering in research and development environment, University of the Witwatersrand, Johannesburg, https://hdl.handle.net/10539/26029

Downloaded from a DSpace repository. https://dspace.org/



Systems Engineering in the Research and Development Environment

Ashlin Ramdas

(Student number: 0408741M)

School of Mechanical, Industrial and Aeronautical Engineering

University of the Witwatersrand

Johannesburg, South Africa.

Supervisors:

Ms Bernadette Sunjka

Dr Duarte Gonçalves

A **research report** submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Engineering.

22 August 2017

DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science in Engineering (Industrial) to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.



A. RAMDAS

……22….. day of …AUGUST….., 2017…….

ABSTRACT

The Research and Development (R&D) environment is characterized by high uncertainties due to the unprecedented nature of the work undertaken. The system engineering approach has been utilized to deal with complexity and technical risks to reduce associated cost and schedule implications. The aim of this research is to investigate *how the application of systems engineering reduces uncertainties and associated risks in the Research and Development environment?*

A case study approach was utilized and a research design was developed according to Yin (2009). The case utilized was the Square Kilometre Array Project as this project is done in an R&D context and applied systems engineering in the project.

It was found that systems engineering does reduce technical risk and uncertainties in an R&D environment. This is achieved through the application of systems engineering technical processes and the utilization of technical management to plan the processes in line with the level of risk. Systems engineering methods and tools are then utilized in the process during project execution. Examples from the case are presented to support this finding. A limitation to this claim, due to the fact that not the entire R&D spectrum was investigated, is that the application of these must be tailored to the associated level of risk. The formality of the process must also be tailored to the level of risk and the size of the project team.

ACKNOWLEDGEMENTS

I would like to thank the International Council on Systems Engineering (INCOSE) South Africa Chapter for hosting the local System Engineering Conference which allowed me the networking opportunity with Square Kilometre Array (SKA) South Africa (SA) project personnel. This opportunity allowed me to do the case study that is presented in this research. I would like to thank Mr Thomas Kusel, the lead systems engineer in the SKA SA project, who provided me with his time for discussion and an interview as well as access to documentation. All this was needed in order to complete this research. I would also like to thank my supervisor and co-supervisor respectively, Ms Bernadette Sunjka and Dr Duarte Gonçalves, for their patience and providing me with the required academic and technical guidance. Lastly I would like to thank my family and friends for their support.

CONTENTS

DECLARATION i

ABSTRACT ii

ACKNOWLEDGEMENTS iii

CONTENTS iv

LIST OF FIGURES vii

LIST OF TABLES ix

LIST OF ABBREVIATIONS x

1. INTRODUCTION 1

1.1. Background 1

1.2. Problem Statement 2

1.3. Central Research Question (CRQ) 4

1.4. Objectives 5

1.5. Research Method 5

1.6. Limitations and Constraints 6

1.7. Report Layout 6

2. LITERATURE REVIEW 7

2.1. Concepts in Research and Development 7

2.1.1. The Research and Development Environment 7

2.2. Systems Engineering Concepts 14

2.2.1. Fundamentals of Systems Engineering 15

2.2.2. Systems Engineering, Uncertainty and Risks 20

2.3. Systems Engineering in the R&D environment – Theoretical Propositions 29

2.3.1. Theoretical Propositions or Hypotheses 31

3. RESEARCH APPROACH 33

3.1. Overview of Case Study Process 35

3.2. Research Design 36
3.2.1. Rationale for a case study 36
3.2.2. Definition of Unit of Analysis and Linkage of Theory to Data 38
3.3. Preparation 54
3.3.1. Case study Protocol 54
3.3.2. Interview preparation 54
3.4. Data Collection and Approach to Data Analysis 58
3.5. Summary of Reliability and Validity 62
4. CASE STUDY INTRODUCTION – SQUARE KILOMETER ARRAY (SKA) PROJECT 64
4.1. Square Kilometre Array Project 64
4.1.1. Selection of SKA South Africa Telescope Development as a Case Study 64
5. RESULTS AND DISCUSSION 67
5.1. Structure of the Results and Discussion 67
5.2. How suitable is a systems engineering approach to a Research and Development Project? (RQ1) 70
5.3. How is the development process structured in the project and why? (RQ2) 75
5.4. How is the technical development process and associated risks managed? (RQ 3) 83
5.5. How are Systems Engineering Methods and Tools Employed in The Project? (RQ 4) 90
5.6. How is the organization as well as project teams structured and managed to deal with the project? (RQ 5) 97
5.7. How does the application of systems engineering reduce uncertainties and associated risks in the Research and Development environment? 101
5.8. Summary of Results and Discussion 104
6. CONCLUSION 108
7. REFERENCES 111

8. APPENDICES 113

APPENDIX A – Square Kilometre Array Case - Interview Transcript 113

APPENDIX B – Interview Consent Form 119

APPENDIX C – Electronic Files - Case Data Coding Evidence- Nvivo 10 Node Report and Case Study Database 120

LIST OF FIGURES

Figure 2-1: Research and Development Activities [6] 7
Figure 2-2: Attributes of R&D Environment [10] 9
Figure 2-3: Henderson and Clark framework for defining innovation [14] 11
Figure 2-4: Definition of Technology Readiness Levels [16] 12
Figure 2-5 R&D Life Cycle [10] 13
Figure 2-6 System Hierarchy [11] 16
Figure 2-7: Generic Life Cycle Stages of a System (ISO 15288:2002) [3] 17
Figure 2-8: Overview of the Systems Engineering Process [15] 18
Figure 2-9: Vee development model [4] 22
Figure 2-10 Illustration of the Waterfall Model [4] 23
Figure 2-11: Illustration of the Spiral Model (Boehm) [5] 24
Figure 2-12: Commitment of costs and cost factors related to change [3] 27
Figure 2-13: Concept Map linking Systems Engineering Concepts to R&D Concepts 29
Figure 3-1 Process to do case study research [23] 35
Figure 3-2 Developing Interview Questions from Research Questions [27] 55
Figure 3-3 Case Study Source Databse 60
Figure 3-4 Theme Nodes used for Coding of Case Study Data 61
Figure 4-1: Rendition of a MeerKAT Dish (Image Credit: SKA South Africa)[27] 64
Figure 4-2: MeerKAT System Breakdown Structure (Credit: SKA South Africa) [29] 66
Figure 5-1: Toulmin's Model of Argumentation [29] 70
Figure 5-2: SKA South Africa Development Process [27] (Credit: SKA South Africa) 72
Figure 5-3: Risk Reduction Approach in System Development Process (Credit: SKA South Africa) [27] 73
Figure 5-4: Toulmin model applicable to RQ 1 75
Figure 5-5 Project Plan Overview [33] 76
Figure 5-6 Example of Trade-off Summary for Antenna Structure [34] 79
Figure 5-7 Detailed Design Process in General [33] 80
Figure 5-8 Structure of Design, Implementation and Integration and Verification Stages [27] 81
Figure 5-9 Toulmin model applicable to RQ 2 82

Figure 5-10: Baselines and Reviews for a Sub-system of the SKA Project [29]..... 83
Figure 5-11 Extract of Risk Assessment in Concept Design Document [34]..... 85
Figure 5-12: Planning of Stages, Baselines and Reviews for the Correlator Sub-system [29]..... 86
Figure 5-13 Toulmin model applicable to RQ 3..... 90
Figure 5-14 High level stakeholder Science Requirement [34]..... 91
Figure 5-15 Use of Simulation to Analyse System Configurations [34] 92
Figure 5-16 Use of Development Models for Risk Reduction [27] (Image: SKA South Africa)..... 94
Figure 5-17 Toulmin model applicable to RQ 4..... 97
Figure 5-18 Organizational Structure of the SKA Project..... 98
Figure 5-19 Toulmin model applicable to RQ 5..... 101
Figure 5-20 Toulmin model applicable to the CRQ..... 104

LIST OF TABLES

Table 3-1: Research methods available to conduct research [23]..... 34
Table 3-2: Linking of theoretical propositions to research questions and data collection 40
Table 3-3: Definition of elements to interpret data..... 45
Table 3-4 Interview Questions with Prompts 56
Table 3-5: Tactics to Ensure Research Validity [23]..... 62
Table 5-1 Summary of Coding references for each node for each source 68
Table 5-2 Elements of Toulmin's Model of Argumentation [30] 69
Table 5-3 Definition of Technical Stages in the SKA Project..... 76

LIST OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
CRQ	Central Research Question
DOD	Department of Defence
GAO	Government Accounting Office
INCOSE	International Council On Systems Engineering
R&D	Research and Development
RQ	Research Question
SE	Systems Engineering
SEMP	Systems Engineering Management Plan
SKA SA	Square Kilometre Array South Africa
TRL	Technology Readiness Levels

1. INTRODUCTION

This section provides a brief introduction and some fundamental concepts in this research in order to provide background and context to familiarise the reader with the research and development environment and systems engineering. A full outline of this research report can be found in 1.7.

1.1. Background

The United States National Research Foundation defines research as;

A systematic study directed toward fuller scientific knowledge or understanding of the subject studied. [1]

A definition for development is also given;

Development is defined as systematic application of knowledge or understanding, directed toward the production of useful materials, devices, and systems or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements. [1]

From the definitions stated above it can be seen that research is focused more on gaining understanding and generation of knowledge. Development then builds further upon this by applying the knowledge created to realize something that meets a specific requirement.

If one looks at the research and development definition, it refers to understanding. With understanding comes information from which something can be inferred in order to explain the subject of study. Rogers [2] states that uncertainty implies a lack of predictability, structure or information. According to Rogers [2] having information is a key factor in reducing uncertainty and is the outcome from scientific research and development (R&D) activities when technology is being developed. This ties in with the definition of development above which states that knowledge and understanding is applied during development.

Rogers [2] also states that development is the process of taking an technology and putting into a form that addresses a need. The need part of Rogers [2] definition of development also ties in with the definition presented above which states to meet a

specific requirement. The need or requirement is something that in turn arises due to a problem a certain stakeholder may have.

From the definitions presented above it can be inferred that the basic purpose of research and development is to build knowledge and to apply that knowledge in order solve problems.

A key interest of this research is the development process in the research and development environment. Particularly the process, methods and tools currently applied in development and to investigate how systems engineering processes, methods and tools may be utilized in this process.

The International Council on Systems Engineering (INCOSE) Handbook [3] utilizes the following definition for systems engineering:

Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.[3]

As stated in the definition above, a goal of systems engineering is producing a quality product that meets customers' needs by documenting requirements, utilizing design synthesis and system validation in the development cycle. If one compares this definition to the definition for development from research and development presented above, similarities are evident. It is the similarities that forms the theoretical propositions for investigating the role of systems engineering in the R&D environment. A more in depth look at the similarities is presented in the literature review in Section 2.

1.2. Problem Statement

In the R&D environment there may be many stakeholders as part of the R&D process. INCOSE handbook defines a stakeholder as *any entity (individual or*

organization) that has a legitimate interest in the system [3]. In this case the output of the R&D process is the key interest of the Stakeholders.

Stakeholders may provide the problem that needs to be addressed and require a solution to this problem by either generating the required knowledge or producing a certain product or service to address this problem. The product, process or service that is the output of development is referred to as a technology that addresses a given problem. Stakeholders might also be governments that may impose policies on utilizing certain technologies or even competitors that may produce a similar technology.

Rogers [2] states that an inventor or developer must not only understand their problems but must also understand the problems of those that will adopt the technology and understand their competitors, government policies and anything that can influence the success of their technology. This understanding is facilitated by a system of information exchange which is highlighted by Rogers [2] as a critical component. It is stated by Rogers [2] that the development process is the exchange of technical information in the face of a high degree of uncertainty.

Due to the unprecedented nature of problems that are usually dealt with in the R&D environment the problem itself may not be clearly stated leading to uncertainties.

These uncertainties arise due to lack of structure and of information [2] as there are many unknowns in R&D. There can be a variety of sources of uncertainty but Ferdowsi [4] states that typically sources of uncertainty can include technical, funding and schedule uncertainties. Ferdowsi [4] also uses these uncertainties and the term risks interchangeably. Uncertainties and the risks they are associated with have been identified by the author as being a key problem in this environment.

The process of progressing from basic research, through to applied research and then onto development is where uncertainties are reduced as more information becomes available and the cause and effect relationships become clear [2].

Shultz et al [6] states that the lack of a structured process in R&D especially creative concept generation results in a large number of trial and error cycles. He identifies this as a shortcoming in development systems. This is further supported by Thomke

[7] who states that not having a process could reduce the performance of an R&D organization and impact cost and speed of development and innovation.

Forsberg [8] states that the application of systems engineering to an R&D project is presented however what is done in terms of a systems engineering perspective is presented and lacks the detail of how systems engineering processes, methods and tools are applied. This is again identified in articles by Thomke and Jaruzelski et al who present investigations into R&D practices in terms of what is done at a high level (such as strategies used by large companies to improve R&D) but do not explore the detail of how this is done and implemented especially considering technology risks such as low technology maturity.

Honour [9] studied the value of systems engineering and one of the shortcomings identified is the following:

"*The practices of systems engineering promise to provide better systems in less time and cost with less risk, and this promise is widely accepted in industry. However, we lack specific evidence regarding the right amount of systems engineering to bring about the best results, as well as the correct timing for the application of system engineering and the identification of those SE tools that are most effective.*"

Thus there is value in investigating how systems engineering is applied in a project and how it impacts project success. While what is being done is presented in the literature the lack of a detailed view on how processes methods and tools are used to improve R&D is identified as a gap in the literature.

1.3. Central Research Question (CRQ)

The definition of the problem in the previous section leads to the following central research question in this research:

How does the application of systems engineering reduce uncertainties and associated risks in the Research and Development environment?

Sub-Research Questions

RQ1. How suitable is a systems engineering approach to a Research and Development Project?

RQ2. How is the development process structured in the project and why?

RQ3. How is the technical development process and associated risks managed?

RQ4. How are systems engineering Methods and Tools employed in the project?

RQ5. How is the organization as well as project teams structured and managed to deal with the Project?

1.4. Objectives

In order to facilitate answering the central research question, the following high-level objectives were defined for this research:

1. Select a project in the research and development environment in order to investigate the research questions.
2. Utilize the research questions to define a framework in order to focus the investigation on specific aspects of the project and determine what data is required.
3. Collect the required data and perform data analysis and interpretation using the framework developed in objective 2.
4. Present the results of the investigation in an appropriate way that addresses the research questions.

The central research question as well as the sub questions forms the basis upon which the units of analysis, as well as the criteria for interpreting the data gathered, was developed.

1.5. Research Method

The research method that was found to be applicable for this research was a case study approach due to the nature of the central research question and objectives. Both documentation and a semi-structured interview formed the sources of data for the case study. Ethical considerations formed part of the development of the interview questions in that the participant was asked to sign a declaration form. The research design and selection of the research method is elaborated in detail in Section 3 of the report.

1.6. Limitations and Constraints

The current research is constrained to investigating only the development (technology development) part of the research and development spectrum due to the similarities in the output of development and systems engineering, that is a product or a service to meet a specific requirement. The research end of the spectrum is not considered. Only one case study was utilized in this research which may be a limitation, however the case that has been selected represents a unique opportunity to study the development of a complex system in a research and development environment that utilized a systems engineering approach. This can be considered the critical case for this research. The rationale for the case study is explained in Section 3.2.1.

1.7. Report Layout

Chapter 1 of this report provides a brief background into research and development, introduces the problem to be investigated and the approach used to research the problem. Some limitations of the research are also highlighted.

Chapter 2 is a literature review of relevant systems engineering literature and current research and development practices. Chapter 2 is concluded with theoretical propositions that form the basis upon which results and conclusions are discussed.

Chapter 3 presents the research design that was used to execute the data collection and data analysis.

Chapter 4 describes the case study that was used as the basis for this research.

Chapter 5 presents the results and discussion for the findings of the research.

2. LITERATURE REVIEW

The literature review presented in this section provides an introduction to concepts in research and development and systems engineering. These concepts are used as a reference in the discussion of this research and in order warrant the evidence found and link them to the interpretation the findings.

2.1. Concepts in Research and Development

2.1.1. The Research and Development Environment

As stated in the introductory section and from the definitions presented, research focuses on the creation of knowledge and development focuses on applying that knowledge to meeting a specific need. According to Rogers [2] research involves both basic research and applied research which is then followed by development which may result in an invention. This is also in agreement with what is presented by Shultz et al [6], that R&D activities may be separated into fundamental research, applied research, technology development and commercialization as illustrated in Figure 2-1.

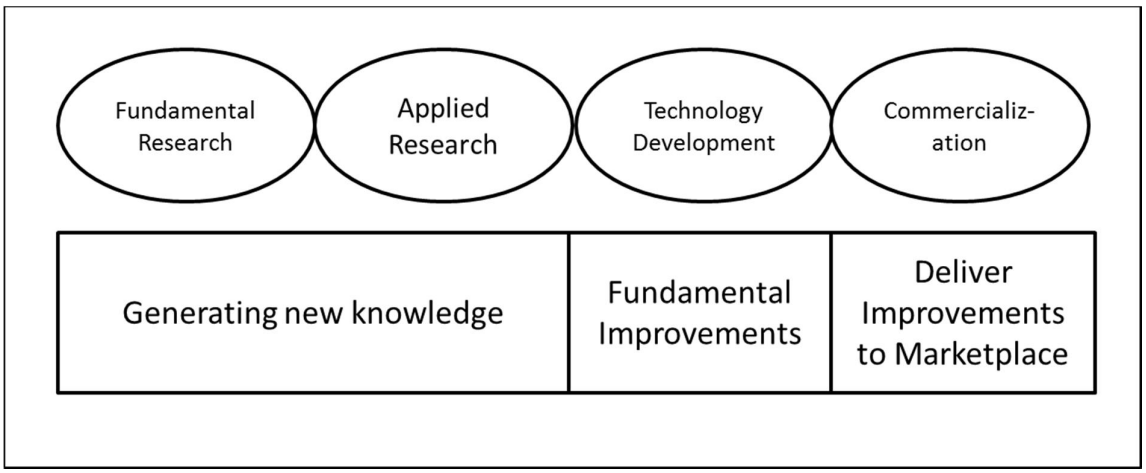


Figure 2-1: Research and Development Activities [6]

Similarly, Forsberg [8] differentiates research by contexts, namely the basic research context, applied research context (which he also calls technology development) and optimization research context. The optimization research differs from the areas mentioned by Rogers [2] and Shultz et al [6]. According to Forsberg [8] optimization

research focuses on the improvement of a system, to the satisfaction of the user, once it has been put in use.

It can be seen that basic research is focused on developing knowledge and has no link to a particular application. At this stage, Forsberg [8] states that the researcher sets the requirements. This is because at this stage uncertainties are high and the outputs of the research are not yet known.

Rogers [2] states that applied research conducts scientific investigations aimed at solving practical problems. According to Forsberg [8] at this stage there is a clearly identified user(s) with stated needs and the objective is to meet those needs. The applied researchers build upon the basic research previously generated [2].

Development is the process of putting the idea into a form that addresses the need of adopters [2]. In the development stage the focus is utilizing the applied research to develop products or processes to meet a defined requirement [1]. Forsberg's definition of applied research encompasses development while Rogers separates research and development.

The process of progressing from basic research, through to applied research and then onto development is where uncertainties are reduced as more information becomes available and the cause and effect relationships become clear [2]. This is in agreement with Figure 2-2 presented by Wingate [10], which shows that the level of uncertainty reduces as research progresses from basic and applied through to development. From Figure 2-2 it can be seen that the nature of the R&D environment is one where there are a high number of unknowns due to the uncertainties which requires multiple iterations in order to progress through each phase.

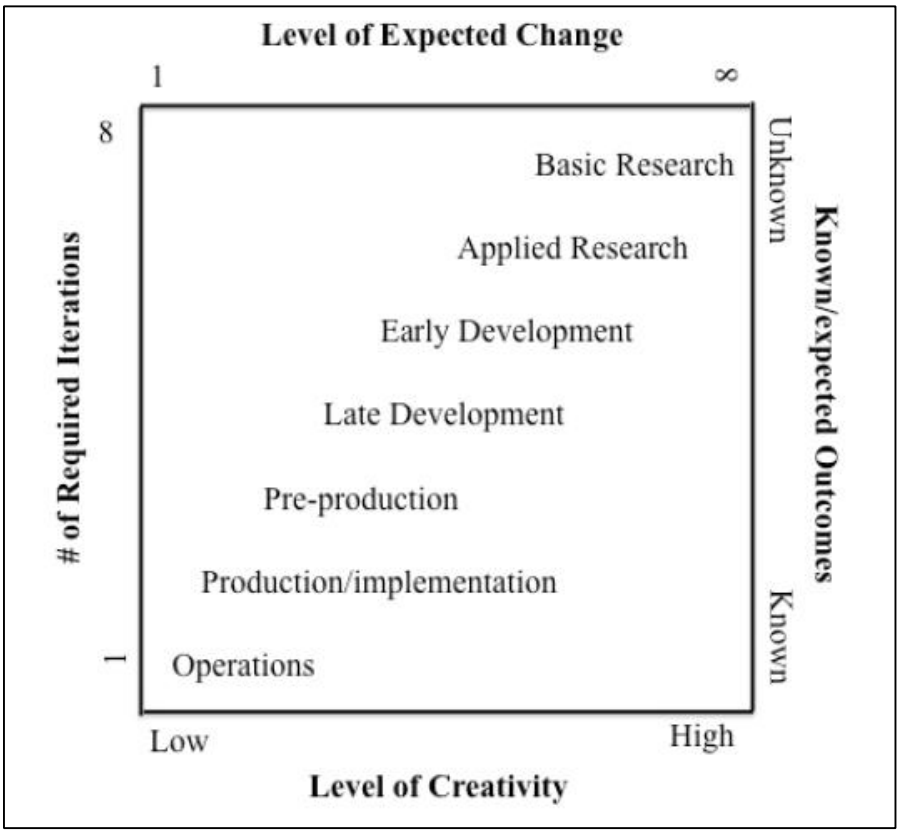


Figure 2-2: Attributes of R&D Environment [10]

Figure 2-2 also shows that the level creativity required in basic research is high. Hitchins [11] states that creativity is about generating new ideas and ways of approaching problems. The high level of uncertainty in basic research due to the high number of unknowns requires a high level of creativity to generate new approaches to solve the unprecedented problems.

The progression through each phase also shows that as uncertainties are reduced there is greater clarity of how to translate knowledge to be applied to solve certain problems. Reduction in uncertainty also allows better definition of a set of requirements allowing a certain technology to be applied to solve a given problem.

According to Forsberg [8] at the stage of applied research or technology development, a user is clearly identified and the objective is to produce a research output that meets this user's need.

According to Rogers [2] a key aspect of technology development is understanding the user or the potential adopters of a technology. As per definitions provided by Rogers [2] an invention is the result of following the R&D process from basic research through to development, however this becomes an innovation when this technology is adopted or used. Thus a key aspect of R&D is inventing technology to solve problems which when adopted by the user becomes an innovation.

Innovation is about perception, if something is perceived as new by an individual and the individual adopts it, it is an innovation from their perspective [2]. In order for an innovation to meet a user's needs it has to follow a process to put it into this form which is called development by Rogers [2]. According to Forsberg [8], a common perception is that a process may stifle invention and creativity however R&D has a very low probability of success if a systematic approach is not followed.

This is in agreement with an article by Jaruzelski et al [12] in which the general manager of research and technology at Boeing states that creative ideas are needed but a rigorous process is needed to "*turn those ideas into dollars*".

Furthermore, following a systematic process in R&D allows one to document research which includes failures and according to Thomke [13] when experimenting with innovations a failure can reveal important gaps in knowledge. Documenting a failure will also allow it not to be repeated.

However, Forsberg [8] also warns that simply following a process is not a replacement for thinking and engineering judgement. Following a process won't definitely result in good R&D outputs but will help in detecting a problem as early as possible.

Henderson and Clark [14] introduced a framework for defining different types of innovation as illustrated in Figure 2-3.

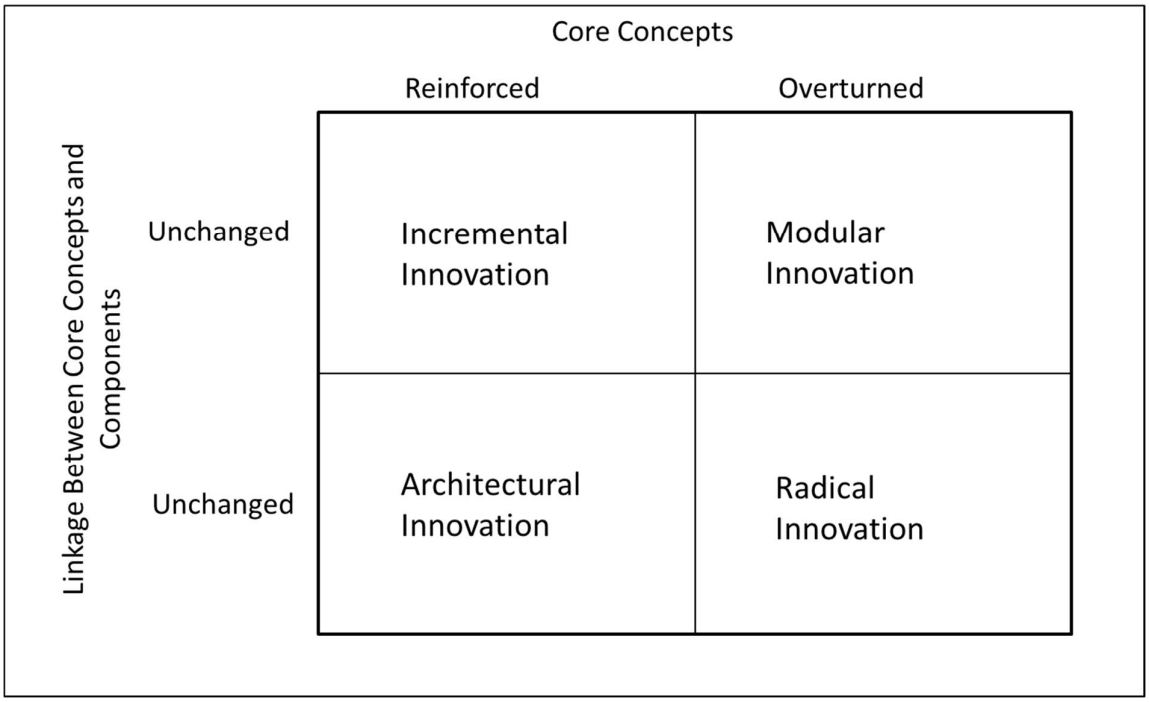


Figure 2-3: Henderson and Clark framework for defining innovation [14]

The model distinguishes the degree of innovation in a product and also links the depth of knowledge that would be required for a given innovation path. According to Henderson and Clark [14] definition of innovation in this manner allows an organisation to understand the usefulness of its existing knowledge when undertaking a certain innovation path. For instance in incremental innovation existing knowledge is further built upon as improvements at a component level are made but the existing architect and design is retained. In radical innovation both the components and architecture are changed and requires an organisation to develop the requisite knowledge in order to achieve such an innovation.

This can be linked to uncertainty and the framework shows that there are higher levels of uncertainty in radical innovations as new knowledge is required in terms of component and architecture when dealing with a new product. According to Henderson and Clark [14] when there is emergence of a new technology leading to a radical innovation there is much confusion and a great deal of experimentation. This period of experimentation ends when a dominant design is achieved and around which an organisation further develops their knowledge. Emergence of a dominant design also shows the technology or product has matured to a certain level due to reduction in uncertainty.

A measure of technical maturity is Technology Readiness Levels (TRLs) which is a scale developed by the United States Department of Defence to measure technology maturity [15]. TRL 1 is the lowest maturity level and represents basic technology research with basic principles observed. TRL 9 is the highest maturity level and represents a proven technology that has been successfully developed in mission operations [15].

The TRL scale is also highlighted in United States Government Accounting Office (GAO) report [16] as shown in Figure 2-4.

Technology readiness level	Description
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and "flight qualified" through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system "flight proven" through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

Figure 2-4: Definition of Technology Readiness Levels [16]

In terms of technology development in the R&D environment the type of development that would be pursued would be a defined as a radical innovation.

Wingate's [10] framework is comparable to the Henderson and Clark [14] framework in terms of the characteristics of the different types of R&D. The axes of Wingate's Framework show the technical challenge and the timeframe for the different types of R&D. As shown in Figure 2-5 the incremental and radical R&D areas represent high technical challenges due to the unknown technology in the incremental case and the

departure from existing capability in the radical case. Each case has associated uncertainties due to these technical challenges which in turn represent an associated set of risks to deal with.

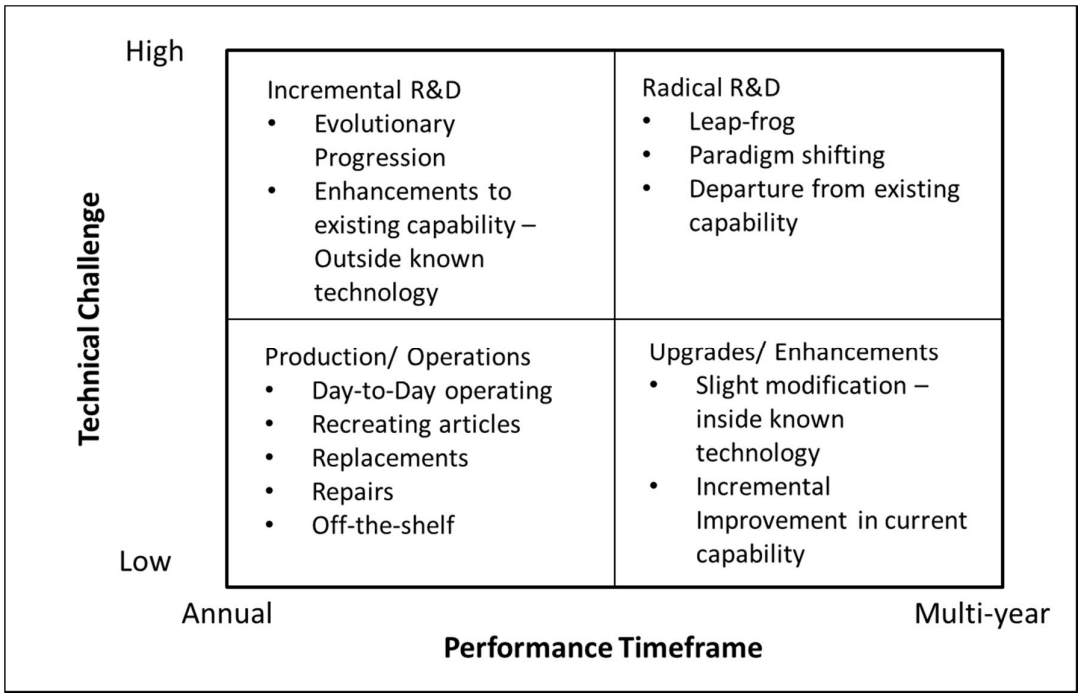


Figure 2-5 R&D Life Cycle [10]

In a product development that follows a system engineering process, certain activities are performed early in the process in order to reduce uncertainties. As mentioned in section 1.2 typically these uncertainties can be due to budget, customer, schedule and technical uncertainties. Each uncertainty has a certain risk associated with it.

In the INCOSE handbook [3] risk is defined as "*the combination of the probability of an event and its consequences*". It is also mentioned that the term risk is generally associated with the possibility of negative consequences. Thus a risk is something to be avoided or mitigated due to negative consequences. When dealing with R&D and innovation especially radical R&D the technical risks are high which could lead to negative results such as poor R&D outputs and wastage of funds. Therefore there is a need to mitigate these risks.

There are some best practices in the literature that deal with risk mitigation in the technology development environment. In a United States Government Accounting

Office (GAO) report [16] some of the following practices which mitigate risk in technology development were identified:

- The use of a metric to measure technology maturity. As stated earlier the Technology Readiness Level (TRL) metric is utilized and is a best practice as it provided a basis for decision making.
- The TRL scale was then utilized for a decision to either continue technology development in an R&D environment or to proceed with full scale development in a product development environment. The more mature a technology the less technical risk results during the product development. This in turn reduces the cycle time and the costs for a given product during product development.
- Splitting of the technology development environment and the product development environment was identified as a best practice. The technology development environment should be free of the pressures associated with product development such as a stricter schedule and less tolerance for failure.
- It was identified as a best practice in commercial companies that there is a decision gate between technology development and product development. There are agreed upon targets between the technology development team and product development team and these forms the maturity criteria to pass through the gate. Utilizing this approach reduced technical risk in product development.

The abovementioned best practices deal with technical risks. The INCOSE handbook states that the primary goal of a system engineer is to reduce risk associated with new complex systems or modifications to complex systems. In the R&D environment the uncertainties that are faced result in risks to the R&D outputs. The methods and tools utilized in system engineering offer an avenue to manage these risks.

2.2. Systems Engineering Concepts

As an outline of this section the following concepts were investigated in the literature:

- Fundamentals of SE
    - Systems thinking and hierarchy
    - Life cycle approach

    - Emergence
    - Complexity
    - High-level SE process
    - The value of Systems Engineering
- SE and risks
    - SE methods and tools to deal with technical risk
        - Method vs tool
            - Methods – Modelling, Requirements analysis
            - Tools – Requirements management software, simulation software,
        - Decision gates and reviews
    - Technical development strategies and technology maturity
        - Evolutionary development
    - Tailoring of the SE process
- Relating concepts and how this leads into the theoretical propositions

2.2.1. Fundamentals of Systems Engineering

The International Council on Systems Engineering (INCOSE) defines systems engineering as follows,

"Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structure development process that proceeds from concept to production to operation. System engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs." [3]

Furthermore a system is defined as,

"A combination of interacting elements organized to achieve one or more stated purposes."[3]

It is evident from the definition that systems engineering considers the problem from a holistic perspective. The basis of this is systems thinking. Kasser [17] highlights that systems thinking considers the system of interest in the context of the system within which it is contained as well as the interactions with other systems that it interfaces with.

As per the definition of a system, considering the combination of interacting elements, each element can form part of the system at different levels in the physical form of the system. Each element could also be a system itself. Hitchins [11] calls this system hierarchy. As stated in the INCOSE Handbook [3] the concept of hierarchy is important when considering decomposition and partitioning of the system. The INCOSE Handbook [3] furthermore defines a system of systems as a system whose elements are *managerially and/or operationally independent systems*.

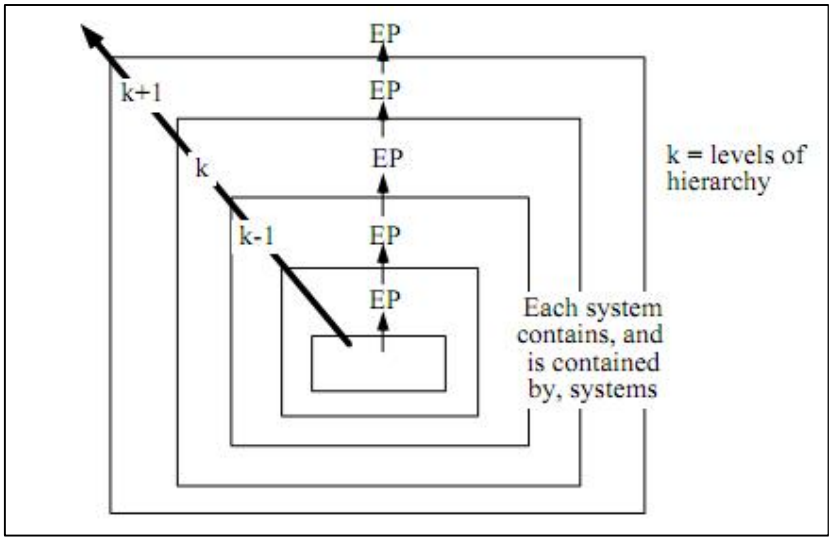
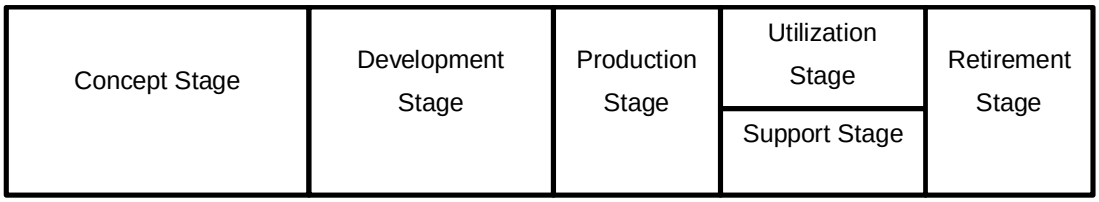


Figure 2-6 System Hierarchy [11]

The concept of hierarchy takes into consideration the system as a whole while staying cognisant of the systems elements. This holistic perspective promotes the understanding that the properties or behaviour that results from a system with many elements is due to the interaction of the various elements and is not attributable to a single element of the system. Hitchins [11] states that this is known as the principle of emergence and is a fundamental concept in systems thinking and in the analysis and development of systems. Considering the system of systems mentioned above the INCOSE Handbook states that the characteristic of emergence associated with a

system of systems can lead to complexity as not all emergent behaviour can be predicted.

A holistic perspective of a system also considers the entire life cycle of the system, which is also evident in the definition of systems engineering. Generic life-cycle stages for a development project as defined in the INCOSE Handbook [3] are shown in Figure 2-7. Between each stage there is a decision point, known as a review, which has defined criteria in order to decide on whether to proceed to the next stage.



These decision points allow risks to be assessed and allow formal approval to proceed to the next stage of development.

Figure 2-7: Generic Life Cycle Stages of a System (ISO 15288:2002) [3]

As a system becomes more complex, that is the more elements and interactions are present, the higher the possibility that unwanted and unpredictable behaviour can emerge. One of the objectives of the systems engineering process is to minimize the unwanted emergent properties of the system and develop the required emergent properties. At state by Whitney et al [18] the approach used in systems engineering is to use the hierarchy principle to decompose a system into more manageable pieces for development. As mentioned earlier this is also called partitioning.

The required emergent properties of the system are generally defined by the stakeholders needs (also known as requirements) which form part of the inputs to the systems engineering process.

Figure 2-8 is an overview of the systems engineering process that is used by the United States Department of Defence.

The first step in the process is requirements analysis. A key input into this process is the requirements which are basically the high-level customer needs. The requirements analysis activity adds value to the stakeholders by ensuring the requirements are of a certain quality and are complete by analysing the problem.

The requirements analysis results in the definition of the systems requirements. In order for the system to meet the requirements the required behaviour of the system must be defined. This is done in the functional analysis (also called functional decomposition) step of the process.

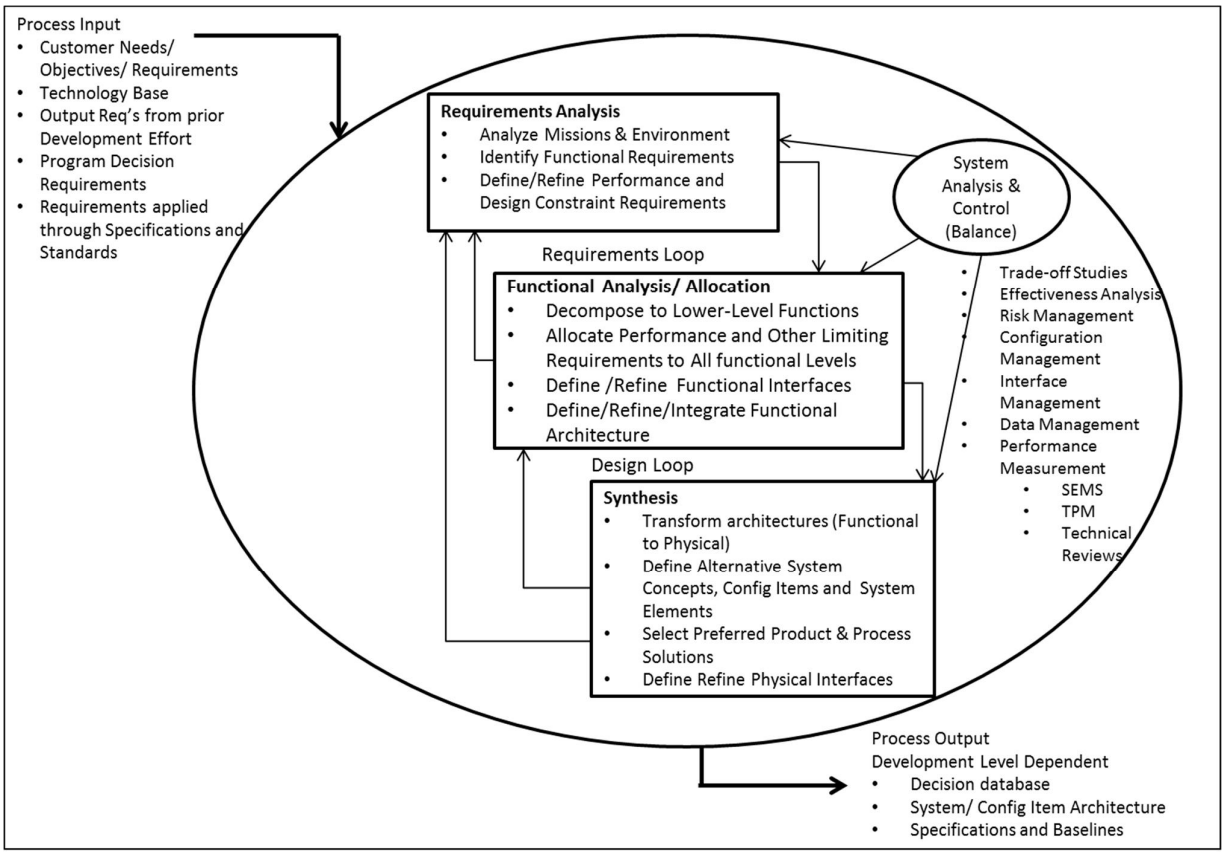


Figure 2-8: Overview of the Systems Engineering Process [15]

From the functional definition of the system, the structure or physical solution is then developed by allocating functions to sub-systems (hardware, software). The functional and physical development of the system culminates in the architecture of the system which is one of the key outputs of the process.

Whitney et al [18] highlight the following about architecture:

- The architecture of the system is the arrangement of components (or sub-systems) and the relationships between them.
- A modular architecture consists of elements that each function independently and interface, with well-defined interfaces, to other elements.

- When a system cannot be decomposed easily and there are many interactions it is said to have an integral architecture.

In Figure 2-8 there can be iterations, indicated by the requirements and design loops, which allow for continuous refinement of the system solution. The system solution is verified to ensure that the system is built correctly and validation is used to ensure that it meets the stakeholders defined needs.

Similarly, as per the INCOSE Handbook [3] the processes mentioned above are referred to as the technical processes of systems engineering. The INCOSE Handbook [3] lists the following technical processes:

- Business or Mission Analysis
- Stakeholder Needs and Requirements Definition
- System Requirements Definition
- Architecture Definition
- Design Definition
- System Analysis
- Integration
- Verification
- Transition
- Validation
- Operation
- Maintenance and
- Disposal

The purpose of the processes as highlighted in the INCOSE Handbook [3] is to enable the "*creation of a sufficient set of requirements and resulting system solutions that address the desired capabilities within the bounds of performance, environment, external interfaces, and design constraints. Without the technical processes, the risk of project failure would be unacceptably high*."

There are also technical management processes in order to manage the technical effort above. According to the INCOSE Handbook [3] the technical management process can include the following:

- Project planning
- Project assessment and control
- Decision management
- Risk management
- Configuration management
- Information management
- Measurement
- Quality assurance

Even though a structured process exists, Forsberg [8] warns that following a process does not replace thinking and will not guarantee a successful output. However the INCOSE Handbook [3] affirms that there is value in systems engineering and that utilizing a systems engineering approach has been shown to be effective in managing the risks associated with complexity and change found in products, services and society.

The INCOSE handbook [3] refers to a study which shows that utilizing systems engineering to a certain point (measured as percentage of system engineering cost versus total project cost) has a positive impact on both cost and schedule overruns. This is also in agreement with Honour [19] who investigated multiple projects to determine the value of systems engineering. The value of systems engineering is explored further at the end of section 2.2.

2.2.2. Systems Engineering, Uncertainty and Risks

The INCOSE Handbook [3] states that a primary goal of a system engineer is to reduce risks associated with new systems or modifications to complex systems. Risk as stated earlier is associated with uncertainty and has negative consequences. Ferdowsi [4] categorises product development uncertainty into the following:

- Budget
- Customer
- Schedule
- Technical

Ferdowsi [4] elaborates that budget uncertainty relates to whether the resources available are sufficient to successfully develop a product. Customer uncertainty

deals with whether a product will meet a customer's needs given these needs can change. Schedule uncertainty is whether or not a product can be developed in the available time and technical uncertainty is whether a product can be developed to meet certain requirements and performance demands.

The INCOSE Handbook [3] similarly defines technical, cost, schedule and programmatic risk. The difference with those mentioned above is the programmatic risk, which is defined as risks that are beyond the control of the project manager. It is also mentioned that technical risk deals with the system itself and high technical risk can generally result in high schedule and cost risk.

Due to the implications of technical risk on schedule and cost a deeper look at technical risks are warranted. In the literature the following have been identified as drivers of technical risk:

- In the INCOSE Handbook [16] a potential failure to meet any requirement expressed in technical terms is a source of technical risk.
- In a United States GAO report [16] it was stated that utilizing technology with low maturity (low TRL level) which would not meet performance requirements results in high risk.
- Ferdowsi [4] states that the rate of change of technology must also be considered aside from just technology maturity as this can introduce a life cycle risk to the product.

In light of the technical risks above, systems engineering has methods and tools available to deal with technical risks. Forsberg and Mooz [20] define technical strategy, in order to deal with technical risks, as consisting of the following elements:

- Development method/model
- Development strategy
- Delivery strategy

The development method or model is utilized to provide a development path taking into consideration the risks associated with the development. The different types of models presented by Mooz and Forsberg are the Waterfall model, the Spiral model and the Vee model.

Buede [21] states that the development method or model is the way the systems engineering process is organized. The Vee model, shown in Figure 2-9, is an example of a development model. Buede [21] further describes the left side of the Vee model as a decomposition and definition process and results in the high-level user requirements being decomposed to system level and then further until component level so that definition of system level and component level specifications can be achieved. The right side of the Vee model focuses on fabrication and assembly of specified components into sub-systems and integration of these sub-systems which results in the final system. At each level verification is performed to ensure conformance to specifications. At the end of the process the system is validated against the user requirement to ensure acceptability to the user.

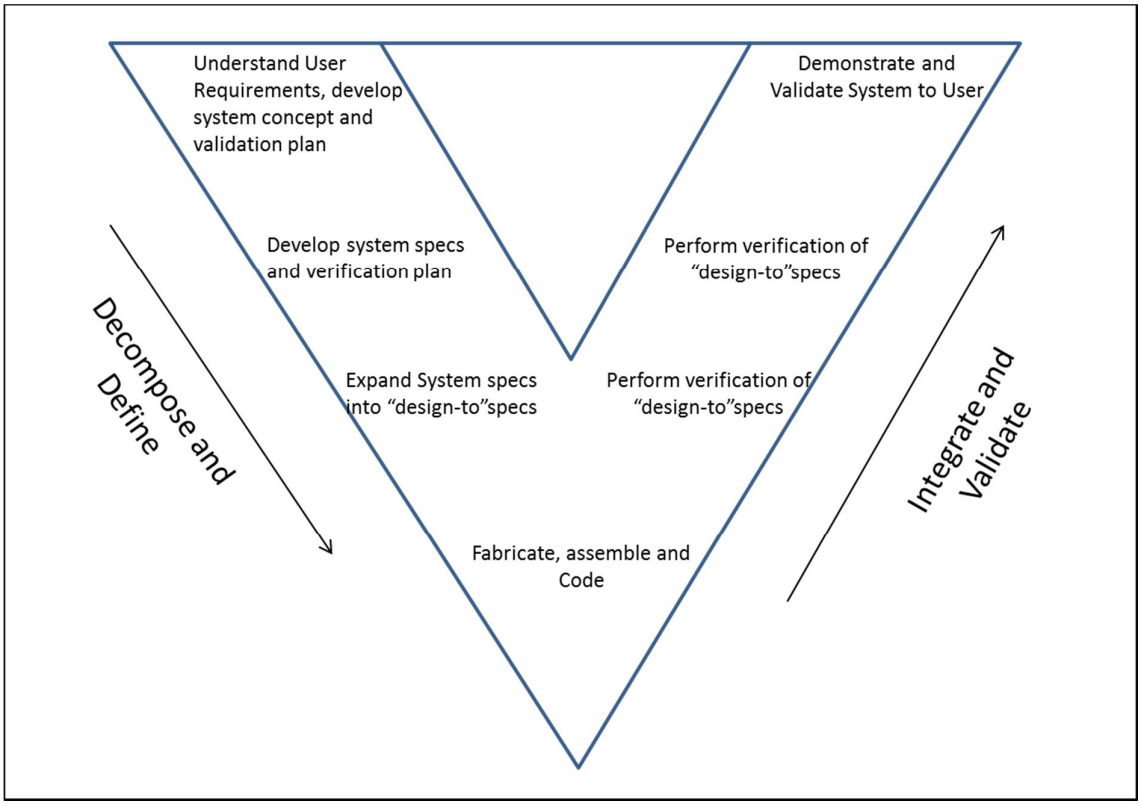


Figure 2-9: Vee development model [4]

The selection of the development model must take into account various development uncertainties such as technical, requirement and budgetary uncertainties. Each model has unique characteristics that can be advantageous or disadvantageous to the system development and has to be considered in the context of the problem to

be solved. For instance, as stated by Mooz and Forsberg [20], the Waterfall model structure shows that each block represents a baseline and work is to be executed sequentially to achieve baseline maturity. An example of a Waterfall model by Ferdowsi [4] is shown in Figure 2-10.

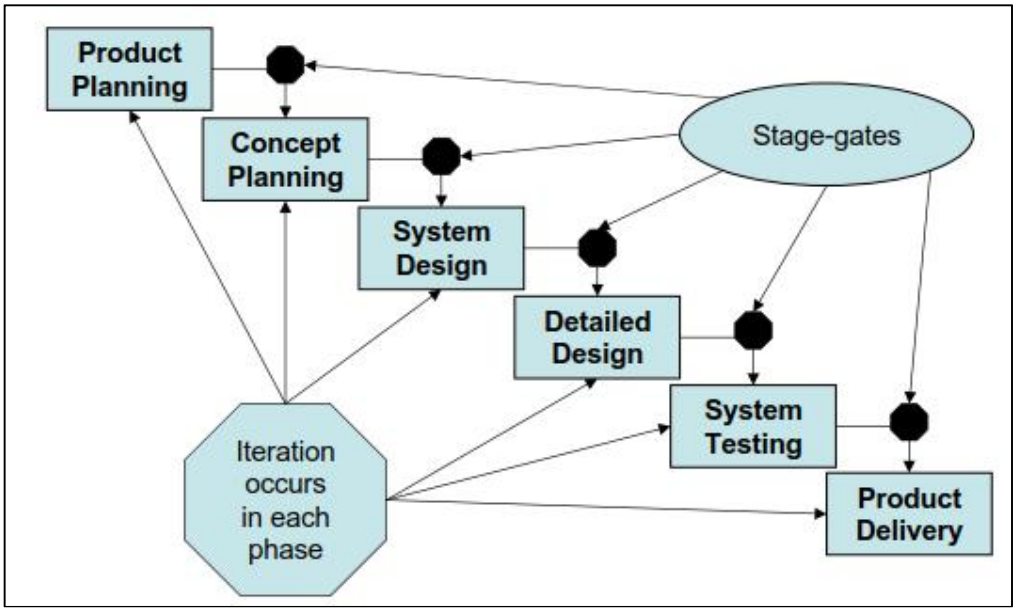


Figure 2-10 Illustration of the Waterfall Model [4]

Furthermore the arrows around each block represent the flow down of requirements and solutions and there can be iteration in order to change a baseline if needed as shown in the figure. The Waterfall model when compared to a Vee model does not incorporate any user involvement or verification and validation activities except at the end.

Mooz and Forsberg [20] describe the Spiral model as a two-dimensional model. The time dimension is the turning of the spiral around the centre point. Each Spiral represents a different risk mitigation and with each successive spiral there should be increased understanding of requirements, technical issues and solutions. As the understanding matures and there is enough understanding of the risks the Spiral model ends with the traditional waterfall model to conclude development. When compared to the Vee model the Spiral model also does not take into account verification and validation amongst other things. An example of the Spiral model as shown by Ferdowsi [4] is shown in Figure 2-11.

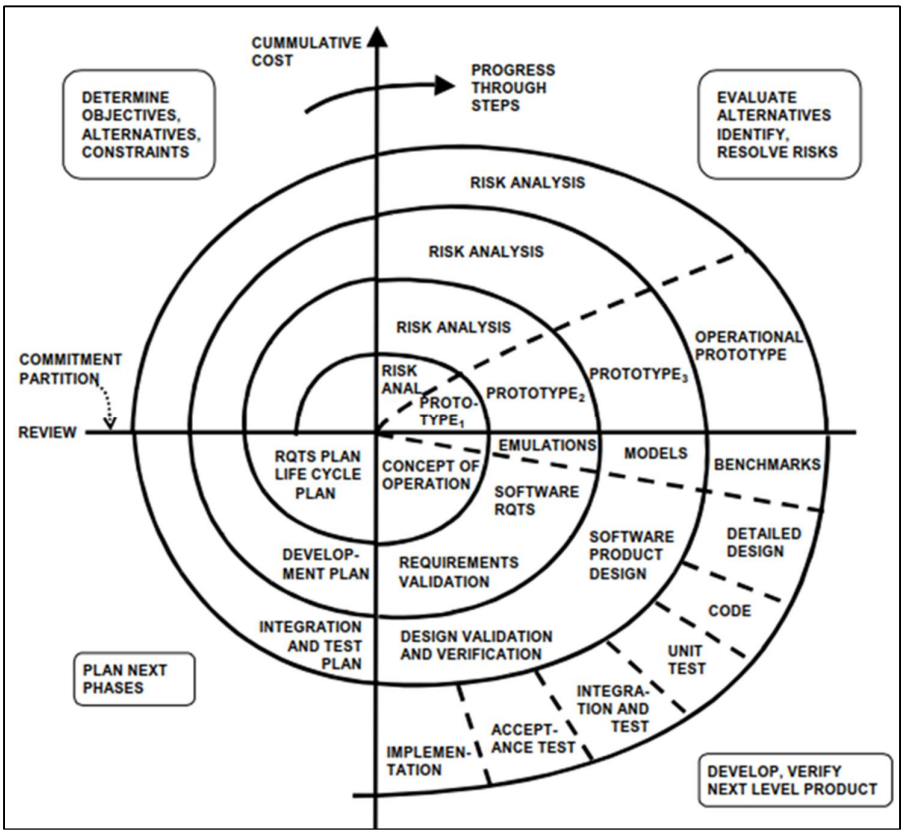


Figure 2-11: Illustration of the Spiral Model (Boehm) [5]

The aspect illustrated with the description of each model is to show that each model has a specific emphasis in the context of developing a system. A Vee model can take into account system complexity and offers an approach to decompose a system while also verifying user requirements while a Spiral model can allow system development and requirements development to take place in parallel. Each model will have advantages and disadvantages which have to be considered in light of the problems to be solved.

To further aid challenges that are faced in system development a development strategy should also be considered. As stated by Mooz and Forsberg [20] the development strategy can be either evolutionary or incremental. Evolutionary processes focus on delivering multiple versions of a solution based on experience with each version. Mooz and Forsberg [20] highlight that an evolutionary development strategy would be selected when requirements are uncertain, the problem environment is dynamic or technology objectives are difficult. Forsberg [8]

further states that evolutionary development directly applies to the research environment.

Mooz and Forsberg [20] describe incremental development as segmented development of solution capability. An incremental development is advantageous when there are technical uncertainties as it delivers an initial capability and allows for additional capability to be added as more advanced technology matures. A development model may be selected and applied to support a given development strategy [20] and is selected based on the problem to be solved.

Taking into consideration the problem and selecting the best process activities for a given level of risk is also known as tailoring. The System Engineering Handbook [3] remarks that tailoring is to ensure the process meets the needs of the project by scaling the rigour of its activities to ensure an acceptable level of risk while reducing project cost.

The tailoring aspects of the systems engineering process can be documented and captured as part of the Systems Engineering Management Plan (SEMP). The SEMP is a document that is drawn up as part of the technical management process and the INCOSE handbook [3] describes the SEMP as the top-level plan for managing the system engineering effort. The SEMP can be used to capture the technical development strategy discussed above as well as the rationale for the strategy in light of the complexities of the project.

A key aspect of the technical management process and what is also outlined in the SEMP are the technical reviews which are conducted to coincide with the various stages of the life cycle shown in Figure 2-7. The reviews can also coincide with decision gates which are points where technical risk is evaluated in terms of established criteria to determine readiness to continue to the next stage or phase of the project.

The SEMP also states what methods and tools may be applied in the process as well. The System Engineering Handbook [3] mentions some of the following methods that can be used to deal with technical risks:

- Modelling and Simulation
- Model based systems engineering

- Prototyping

There are various tools and speciality engineering that are also utilized as part of the systems engineering process such as requirements management tools, model based system engineering and software tools and computer aided design tools.

The utilization of methods and tools are to reduce technical uncertainty. In technology development there is much technical uncertainty because the core concepts of the technology have not yet been established and effort is put into maturing the technology so that a dominant design can be established [14]. Henderson and Clark [14] characterise a dominant design as a design where the design knowledge in terms of allocation of functions to components and the architecture and integration of the components has been firmly established. Once a dominant design prevails the focus shifts to refinements at lower levels since the design choices at higher levels have already been fixed. Another way that this is stated is that a radical innovation creates a new design path at the highest level [18]. Decisions made early in the development process fix design choices at higher levels and it has cost and time implication to then change these choices.

The effect of committing to design decision early in the development process and the cost risk associated with changing a design decisions at a later stage also relates to what is stated in the INCOSE Handbook and is illustrated in Figure 2-12.

The further along the design process progresses, the more difficult and costly it becomes to affect change in the design. This directly relates to the case for the value of systems engineering. The earlier that risks are addressed in the design and development process generally results in less costs and schedule increases due to changes.

This alludes to the notion that during the conceptual and design phases where higher level design decisions are made, especially with regard to the system functions as well as the architecture, a good understanding of the technologies to be incorporated into the design is required.

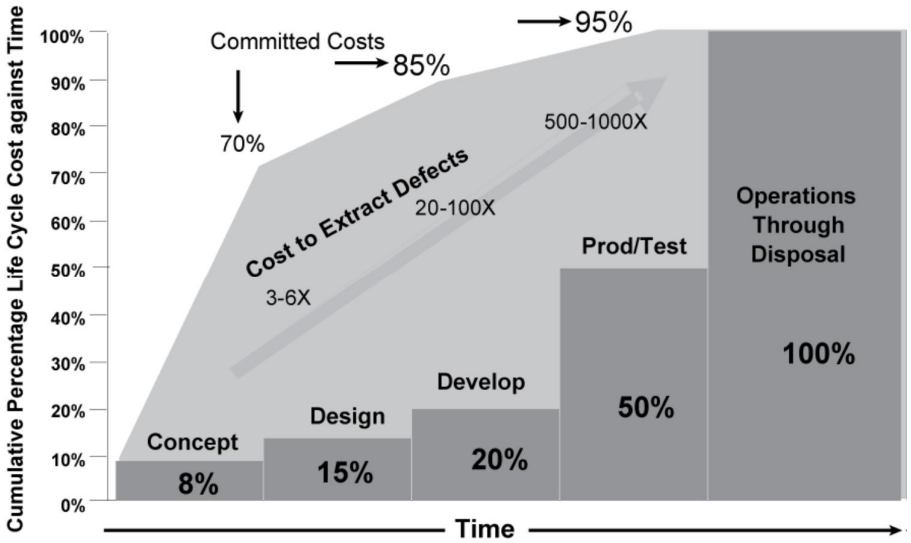


Figure 2-12: Commitment of costs and cost factors related to change [3]

Buede [21] also identifies the following as value adding by systems engineers:

- Systems engineers find the best solution in a given solution space by utilizing trade studies to resolve conflicting stakeholder requirements.
- Systems engineers act as a communication interface between stakeholders and various disciplines in a complex project.
- Value is added by risk reduction in which systems engineers understand the different levels of uncertainty associated with design alternatives. In this way the uncertainty of achieving the required level of performance with a given technology is reduced.

Honour [19] has investigated the value of systems engineering by studying various projects and the following are some observations that were made as part of the study in respect of the value of systems engineering and impact on cost and schedule risk reduction:

- That increasing the level of system engineering effort does have a positive effect on cost compliance and schedule compliance.
- The optimum value of system engineering effort is in the range 15% to 20% of the total cost of the project.

In another study Honour [9] further states that the application of systems engineering correlates to shorter schedules by approximately 40% and lower development costs

of approximately 30% or more. From Honour's [9] research it can be seen that from a systems engineering perspective the primary goals of a project are to develop the optimum system to meet the user's needs within a scheduled time while minimizing cost. From this perspective the general definition of a failed project could then be a project which meets any one of the following conditions:

- failed to meet the users requirements
- was too costly (over the planned budget)
- was not delivered within the scheduled time.

In order to gain greater insight into how systems engineering can add value and promote project success, the actual causes that lead to these conditions have to be considered. A study by the Standish Group [22] identified the following top 10 factors as contributors to projects failing:

1. Incomplete requirements
2. Lack of user involvement
3. Lack of resources
4. Unrealistic expectations
5. Lack of executive support
6. Changing requirements and specification
7. Lack of planning
8. Didn't need it any longer
9. Lack of IT management
10. Technical Illiteracy

Looking at the top 10 list of factors, it can be seen that there are multiple areas that are directly linked to systems engineering concepts. As presented earlier in this section, systems engineering development models, such as the Vee model, promote planning, user involvement, elicitation of user requirements and management of changes in requirements. The use of system engineering methods such as requirements analysis to ensure a complete set of requirements is another instance. The application of systems engineering as highlighted can add value in contributing to project success by reducing technical risks and thereby contributing to lower schedule and cost risks as highlighted by Honour [19].

2.3. Systems Engineering in the R&D environment – Theoretical Propositions

Figure 2-13 below links key systems engineering concepts to the R&D environment:

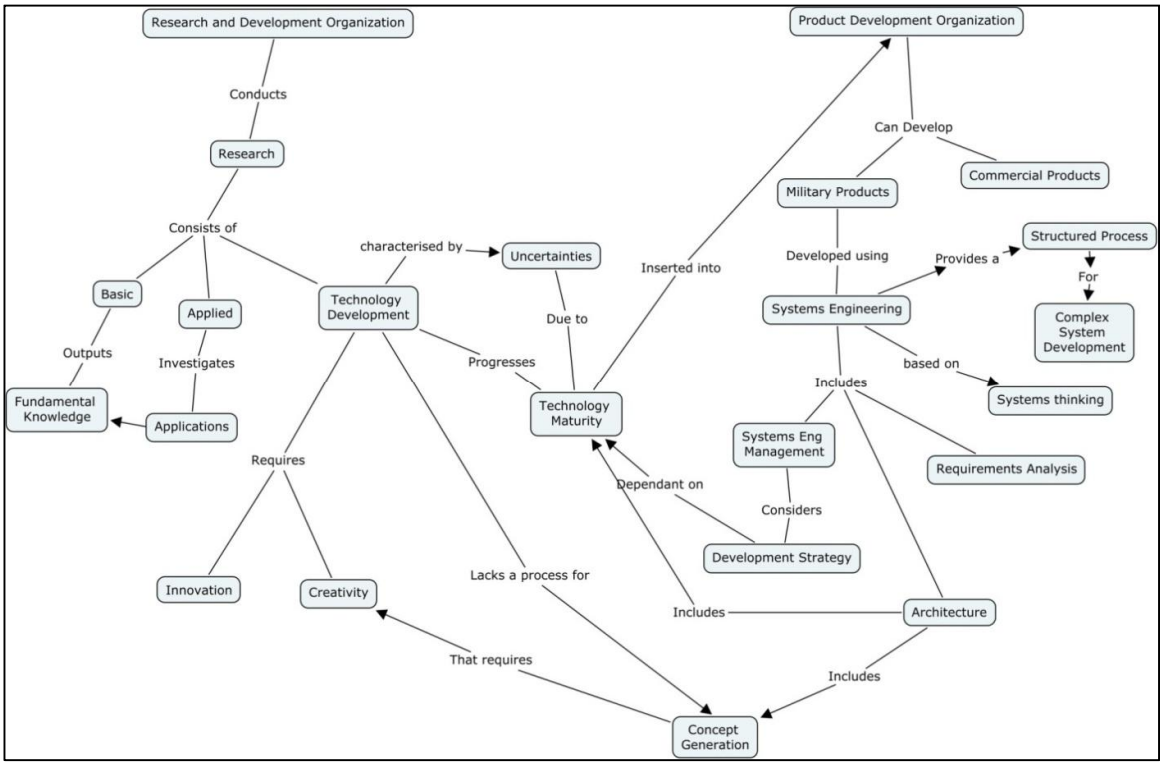


Figure 2-13: Concept Map linking Systems Engineering Concepts to R&D Concepts

The concept map is a schematic representation of the key concepts from the literature. It was constructed by the author in order to show the relationships between systems engineering concepts and the characteristics of the research and development environment. The concept map reveals that there are specific concepts from systems engineering that are related to the research and development environment such as considerations of technology maturity and technical uncertainties. The concept map was also used to reveal any relationships that could be utilized to develop theoretical propositions.

The concept of technology maturity is elaborated further to explain why it is an important life-cycle consideration in the design and development of a system. The concept of a development strategy is also introduced as this defines a path to be

followed during the development in order to deal with uncertainties. Uncertainties that have been identified in the literature include operational requirements, technology obsolescence, budget and the operational environment [4].

As stated by the United States GAO [16] technology maturity is an important factor in reducing development cycle times and in reducing technical risk. As a technology matures the less susceptible it is to changes allowing for easier incorporation into the development process [6]. In the concept map it is shown that technology maturity is also considered as part of the systems engineering process in architecting.

Technology Readiness Levels (TRLs) which was introduced earlier provides a defined measure of maturity allows for decision making during technology development which can influence the technical development strategy.

In the technology development environment where there is inherent technical uncertainty an evolutionary development strategy, together with an appropriate development model that considers the level of technology maturity, can potentially provide a structured approach to mature technologies.

Another important consideration is the rate of change of technology. The life cycle of a technology is far shorter than that of a product as highlighted by Ferdowsi [4]. In considering the impact of a new technology holistically, the changes in the product into which it is being inserted must also be considered. Whitney et al [18] state that as a product matures improvements in technology generally take place at lower levels because at higher levels initial architectural decisions have already been made and can be difficult to change. A radical change in technology may influence the interface of a technology to the product it is being inserted into and may require changes in the product itself. Architectural considerations of the technology must be made and this is an inherent part of the systems engineering process as shown above. This also further strengthens the argument raised with Figure 2-12 that applying systems engineering early in the design process can reduce costs and save time as the development progresses through the life cycle.

Forsberg [8] highlights the following potential risks of applying systems engineering in an R&D environment:

- The systems engineering process will not turned flawed concept into good research.
- The creative environment can be destroyed by focussing on the formal process aspects of system engineering utilized in large projects which can result in excess documentation.

Forsberg however does state that utilizing a system engineering process will reveal flaws in a concept earlier which can allow action to be taken. He further states that the key to success is to adopt the logic of systems engineering and to tailor the formal process to fit the environment to which it is being applied.

A system should be developed to be flexible to incorporate evolving technology. One approach that is highlighted United States DoD [15] to allow a system to be flexible and adaptable to technology changes is an open system approach. An open system approach promotes the use of future technology advancements by emphasizing flexible interfaces and maximum interoperability.

2.3.1. Theoretical Propositions or Hypotheses

Based on the literature review some theoretical propositions or hypotheses considered in this research are the following:

1. There are perceptions by researchers that applying a process in R&D will stifle creativity but a rival view according to Forsberg [8] is that there is very little chance of success of R&D without a structured and systematic process. A structured approach will help in detecting problems as early as possible.
2. A primary goal of systems engineering identified according to the INCOSE Handbook [3] is to reduce risks associated with new systems or modifications to complex systems. The technical processes allow the realization of a system that meets stakeholder requirements while considering risks. The risks can arise out of budget, schedule, customer and technical uncertainties as broadly identified by Ferdowsi [4].
3. The systems engineering process as well as the methods and tools that have been identified in the literature are geared toward planning for and managing technical risks. Reducing technical risk has an impact on project costs and schedule as highlighted by Honour [19].

4. The INCOSE Handbook [3] affirms that there is value in systems engineering and that utilizing a systems engineering approach can be effective in managing the risks associated with complexity and change found in products, services and society.
5. Systems engineering is a requirements driven process with high level requirements usually defined by a customer. According to Forsberg [8] in an R&D environment the researcher or technology developer has to set the requirements when no customer is defined.
6. It has been identified in the literature, as highlighted in the INCOSE Handbook [3], that system engineering is recommended to be used early in the development process as that is where critical design decisions are made which become costly and time consuming to change later in the project.
7. From Figure 2-13, which was derived from the literature, it can be seen that technology maturity is a common concept between technology development and the development strategy used in systems engineering. Technology maturity has been identified in the literature as a key metric upon which project decisions are made and can impact development costs and schedule. Furthermore technology maturity also has to be considered when selecting a development strategy as highlighted by Mooz and Forsberg [20].
8. As per the Henderson and Clarke [14] model, Figure 2-3, and Wingate's [10] framework, Figure 2-5, when dealing with new technology and especially radical R&D an organisation has to develop new knowledge and new capabilities to reduce the uncertainties associated with this new technology.

3. RESEARCH APPROACH

The structure of the central research question (see section 1.3) which focuses on how systems engineering is applied was used to guide the selection of the research method. In the application of systems engineering there is a process utilized and various activities performed and methods applied to a project. Thus there are many aspects to be investigated and much of this is not captured quantitatively using measureable metrics. The context of the project, that is the project environment and the focus of the project itself, impact the application of the process and interact in ways that may not be measured easily. Thus there are many variables to be considered due to the complex interactions than is currently measured by project performance metrics.

In engineering research usually a laboratory experimental setup is utilized to study a phenomenon with quantitative measurements and statistical analysis. However in researching a complex project environment to understand how and why activities are performed as described in the research question there are not usually quantitative measures defined. However, social science offers methods that can be utilized to investigate a project environment.

As highlighted by Yin [23] there are various social science research methods available in order to understand complex social phenomena. In Table 3-1 Yin [23] highlights the various research methods and the type of research that the method promotes.

Table 3-1: Research methods available to conduct research [23]

METHOD	FORM OF RESEARCH QUESTION	REQUIRES CONTROL OF BEHAVIOURAL EVENTS	FOCUSES ON CONTEMPORARY EVENTS
EXPERIMENT	How, why?	Yes	Yes
SURVEY	Who, what, where, how many, how much?	No	Yes
ARCHIVAL ANALYSIS	Who, what, where, how many, how much?	No	Yes/No
HISTORY	How, why?	No	No
CASE STUDY	How, why?	No	Yes

As seen in Table 3-1 in research that involves the inquiry of how and why, the experiment, history and case study approaches can be considered. However, the experimental method requires control over behavioural events and the history does not focus on contemporary events. In the current research of an R&D project the researcher had no control over the project and the project was a contemporary event at the time of the execution of the research. Thus a case study method was selected to do this research as it promoted the form of inquiry for this research as well as the limitations that the researcher has no control over the event being studied and that the event is current. The full rationale for the case study approach follows in section 3.2.1.

3.1. Overview of Case Study Process

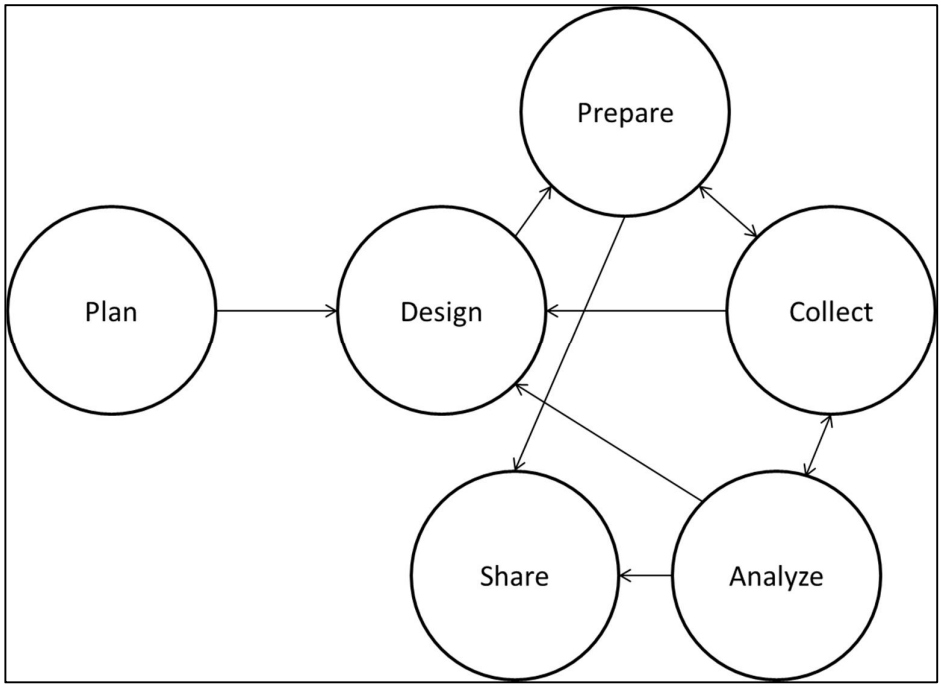


Figure 3-1 Process to do case study research [23]

As illustrated by Yin [23], Figure 3-1 shows a high level process for carrying out case study research. As a brief introduction (which will be elaborated in the sections to follow) the following high level considerations were made in respect of the elements of the process:

- Research Design
  - Rationale for a case study
  - Research questions
  - Theory development and propositions
  - Definition of the units of analysis
  - Logic linking the data to the theoretical propositions
  - The criteria for interpreting the findings
- Data Collection
  - Development of interview questions from research question
  - Data collection protocol – interview procedure and ethical considerations
  - Creating a database for the sources of evidence
- Data Analysis and Presentation (Part of the results and discussion section)

- Utilization of a tool for data analysis
- Reporting of the case study findings in terms of the definition of the criteria defined

3.2. Research Design

3.2.1. Rationale for a case study

Yin [23] describes the following characteristics that make a case study approach applicable:

- A contemporary phenomenon is being investigated in its context
- The boundaries of the phenomenon and context are not clearly evident

The case study approach was found to be applicable in the current investigation since the study of the processes, methods and tools that are applied in a development project cannot be investigated independently and is dependent on the context of the development itself. The complexity of the development influences the development process and ideally there should be tailoring of the process. The boundaries of the problem are also not clear since there are many variables (complex problem environment) that influence the development. The problem to be investigated is not quantitative in nature but qualitative which further makes a case study approach applicable.

Yin [23] further states that the following components of a research design are especially important to case study research:

- a study's questions
- theoretical propositions
- unit(s) of analysis
- the logic linking the data to the propositions
- the criteria for interpreting the findings

In this research a central research questions was developed as stated in the introduction. A literature review was conducted in order to investigate theoretical propositions relevant to the research. These theoretical propositions or hypotheses are presented in section 2.2.3.

Prior to delving into the detail of the logic linking the data to the propositions the following aspects were also considered as part of the research design.

- Case study design – single vs multiple cases
- Type of case study – Exploratory, explanatory or
- Aspects of case study quality

In this section the considerations of the above will be explained but when looking at the case in detail, in Section 4 of this report, the actual evidence to support the reasoning will be presented. This is done in order not to duplicate effort.

In terms of case study selection Yin [23] highlights that single or multiple cases can be utilized for case study research and the following are highlighted as some of the reasons that justify considering single case study research:

- The case considered is the critical case
- The case considered is an extreme case or unique case
- The case considered is a representative or typical case
- The case considered is a revelatory case

Yin [23] states that the critical case is a case where there is a set of theoretical proposition and a set of conditions under which they are believed to be true.

The case in this research was selected as it represents the critical case in relation to the theoretical propositions and the defined central research question. The main purpose of the investigation is to determine how systems engineering is applied in a project in the research and development environment. The case in this research will be referred to as the Square Kilometre Array (SKA) case and it can be considered the critical case as it a project undertaken in the research and development environment which applied a systems engineering approach in the execution of the project. Therefore the project is an ideal case study for the current research.

Further reasons as to what made the case feasible in this research are the following:

- The access to data was not restricted or classified
- The point of contact that provided access to the case study documentation also agreed to be interviewed which provided an alternative source of evidence. As highlighted by Yin [23] utilizing multiple sources of evidence

during data collection strengthens construct validity which is a good practice to ensure a case study approaches quality.

Irrespective of the justification for a single case Yin [23] states that a vulnerability of the single case is that as it is unpacked it may turn out to not be the case it was originally thought to be. In the current research this was mitigated as the author was exposed to many details of the SKA case as many aspects of the project were presented at a conference. This allowed sufficient time to be familiar with the details of the project prior to selecting it as the case for this research.

Another vulnerability highlighted by Yin [23] of the single case approach, as opposed to a multiple case approach, is that replication cannot be used to strengthen conclusions. Replication as defined by Yin [23] is when multiple cases being studied predict similar results (literal replication) or contrasting results but for predicated reasons (theoretical replication). However as highlighted by Yin [23] the key to making inferences in case study research is based on analytical generalization, which is comparing results from the case study to an existing theory from literature. This can be achieved irrespective of using single or multiple cases. To avoid the replication vulnerability a set of hypotheses from the literature is clearly stated which will form the basis for comparisons to the evidence. In order to strengthen the analysis one of the techniques for case analysis suggested by Friedman and Sage [24] would be to use Toulmin's Logic Model also called Toulmin's scheme of reasoning. This model will be described in the detail in the results section. It ensures logic in arguments and that the necessary evidence is presented to support those arguments. Such a model was used in the discussion and will be presented further in the results and discussion section.

3.2.2. Definition of Unit of Analysis and Linkage of Theory to Data

Yin [23] states that the selection of the unit of analysis should complement the central research question and this approach was followed in this research. In this research a single case study with a multiple units of analysis was used referred to by Yin [23] as an embedded single case design. The main unit of analysis in this research is defined as the SKA project and the sub units of analysis are linked to the defined research questions. Sub units were defined in order to investigate some detail and to obtain further coverage of aspects contained at lower levels within the

project. The research questions and theoretical propositions aided development of the sub units of analysis as well as the variables in order to focus the research further.

To assist with the data gathering, sub-questions were developed from the central research questions to allow a more focused approach to data gathering. Table 3-2 was developed to assist with data gathering as well as to capture the rationale behind the questions. This table also provides the link to the theoretical propositions. The framework presented in the table was adopted from an approach proposed from Maxwell [27] for linking research questions to methods and other data. The first question in the table represents the central research question introduced earlier and the remaining questions are sub research questions in order to break it down further into manageable pieces for data collection.

Table 3-2: Linking of theoretical propositions to research questions and data collection

What do I need to know?	Why do I need to know this?	What kind of data will answer the question?	Where can I find the data?	Whom do I contact for the information?
How can the application of systems engineering reduce uncertainties and associated risks in the Research and Development environment?	This central research questions was defined to direct the case study investigation towards understanding how the system engineering approach is utilized in a project in the R&D environment. From Hypothesis 2 (section 2.3.1) a key aspect of systems engineering is risk reduction which is why the focus of the question is on uncertainties and risks.	Data regarding the nature of the risks and development uncertainties faced in a project in an R&D environment. Data relating to how the systems engineering process was applied to the R&D project and the effect on technical risks reduction.	From organizations existing system engineering management plans and other project documentation. From people who have experience in going through the process of R&D to develop technologies.	Project Manager or System engineer manager Or a scientist.
How suitable is a systems engineering approach to a Research and Development Project?	Hypothesis 1 (section 2.3.1), refers to the approach of systems engineering and the view of its suitability to an R&D environment. This sub question was derived from the central question in order to further focus the investigation on the complexity and risks faced in an R&D project and if Systems Engineering is applicable to	Qualitative data regarding the context of the development environment as well as the type of development and the specific methods and tools used	Personnel involved with or managing the technology development. Development plans and other engineering reports.	Project Manager or System engineering manager.as well as scientists.

What do I need to know?	Why do I need to know this?	What kind of data will answer the question?	Where can I find the data?	Whom do I contact for the information?
	this.	during the development. The management of the development is also needed.		
How is the development process currently structured and why?	Hypotheses 4, 5 and 6 (section 2.3.1) refer to the use of the System Engineering process. This sub question was defined in order to focus on the process utilized in a project in the R&D environment. How the process is structured and tailored will also provide insights into the depth of understanding of the application of systems engineering to the given problem.	Data about processes that are actually applied and how it is structured to meet the needs of the R&D project.	Project documentation with data describing the process used.	Project Manager or System engineering manager.
How is the technical development process and associated risks managed?	Hypotheses 2, 3 and 7 (section 2.3.1) refer to the planning and management of the systems engineering process to address technical, budget, schedule and customer uncertainties. This sub research question was defined to understand how the system engineering process is managed in	Qualitative data regarding process tailoring and project planning.	Project plans and systems engineering management plans.	Project manager and Systems engineering managers.

What do I need to know?	Why do I need to know this?	What kind of data will answer the question?	Where can I find the data?	Whom do I contact for the information?
	an R&D project and what considerations are made in the planning and management of the process to address risks.			
How are systems engineering Methods and Tools employed in the project?	Hypothesis 3 (section 2.3.1) refers to methods and tools that are used within the systems engineering process. This research question was defined to investigate how the systems engineering methods and tools are used in the R&D project to address technical risks.	Qualitative data regarding the specific methods and tools used during the project as well as the management of the development process.	Personnel involved with or managing the technology development. Development plans and other engineering reports. Trade-off studies. Other research papers or investigations.	System engineering manager.as well as scientists.
How is the organization as well as project teams structured and managed to deal with the R&D project?	Hypothesis 8 (section 2.3.1) refers to the organisational knowledge and capability required to undertake projects with high technology uncertainties. This question was defined to also investigate how the organization that is responsible for the project may influence the project. Furthermore this question was also defined to investigate how the project	Data regarding the structure of the organization, stakeholders of the organization as well as structure of the project team. Data on how knowledge and the capability to handle new	Personnel involved in management. Management documentation plans.	Program manager or System engineering manager

What do I need to know?	Why do I need to know this?	What kind of data will answer the question?	Where can I find the data?	Whom do I contact for the information?
	team was organized and worked together to execute the project.	technology was managed to meet project requirements.		

The hypotheses were also used to provide direction to the research in order to ensure that the research would be feasible to conduct.

In order to link the hypotheses to the data to be collected for the research, the unit of analysis was further broken down into sub-units of analysis as per the embedded single case design. The sub-units of analysis were defined to be aligned with the sub-research questions as this provides a logical link when obtaining evidence from the analysis and then relating them back to the questions to be answered. The specific elements or variables defined in the table provide a way in which to interpret the evidence when doing the data analysis and will be utilized as key words when coding the data. Table 3-3 presents the definition of these elements.

As suggested by Yin [23], a case study protocol was designed to gather research data. This is presented in section 3.3.

Table 3-3: Definition of elements to interpret data

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
SKA PROJECT	**CONTEXT** **(Linked to RQ 1)**	Person interviewed	- Qualification/ area of specialization - Role of person - Years of experience	Provides validity to the interview process and the outputs.
		Type of development and environment	- Applied research or technology development - Product, process or service. - Complexity	Provides context of the development environment. The complexity is considered to arise from the following: - System elements and interfaces - Development environment (interdisciplinary nature of the development) - Operating environment
		Innovative areas	- Component level - Architectural level - Both component and	Provides information to define the level of innovation according to Henderson-Clark model. (Incremental, modular,

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
			architectural innovation - Novel in application	architectural or radical)
		What type of system? (System Hierarchy)	- New product/process/service - Improvement - Critical Technology element? - No of Interfaces	This would provide an idea of the system in its context and the system complexity.
		Project Budget	- High vs. Medium vs. Low -	Provides context when analysing results and possibly enable transferability of research results to other similar contexts.
		Project time constraints	- Weeks/Months/Years	Provides context when analysing results.
		Key project challenges (development uncertainties)	- Resources (budget and people) - Stakeholders (requirements) - Schedule - Technical	This provides an understanding of the uncertainties and allows one to link this with the development approach (to investigate insight of developer into use of SE development tools). [Uncertainties from

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
			- Changing environments	literature].
	PROCESS **(Linked to RQ 2)**	Process activities	- Stakeholder Req. definition - Requirements Analysis - Architecting - Implementation - Integration - Verification/validation - Change management - Operations and logistic support	What process stages where used?
		Problem definition	- Yes/No - Concept of operations	To determine if the problem was defined at the start of the process?
		Requirements Analysis	- System life cycle considerations - Elicitation techniques (if any used) - Interaction with customer	To determine if requirements were analysed and if there is any interaction in this regard with the client.

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
			- Modelling behaviour and structure - Specification writing	
		Architecting	- Architecture drivers - Structure - Behaviour - Internal interfaces - Analysis of alternatives	How was the required system behaviour determined? (Links to modelling) Was there a process that considered alternative components to satisfy required system functions?
		Implementation/ manufacturing	- How was the design realized? (fabrication and use of specialists) - How this was captured – design documents.	What
		Integration	- Was integration considered? - Did the technology have to be integrated into a larger system? - Interface definition	Provides insight into integration and definition of interfaces. (cross refer to modelling and req analysis). Was COTS equipment to be integrated?

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
			- COTS equipment	
		Process outputs	- Knowledge - Process/Product/Service? - Documentation	Provides frame of reference when interpreting results.
		Process Quality Measures	- Engineering changes - Re-design - Verification - Validation	How was development quality measured if at all?
		Process Cycle time	- Cycles until convergence to final output.	Provides a measure as to the development time.
	METHODS AND TOOLS **(Linked to RQ 4)**	Modelling and simulation	- Type of modelling used - Purpose of modelling and simulation in development - Prototypes	To determine the role of modelling and simulation in R&D and to compare to with product development. This may also show the level of secondary technology and its impact on development of primary technology.
		Computer based Design Tools	- CAD	

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
			- Software development	
		Requirements Management Tools	- Was requirements management software utilized?	
		Prototyping	- How many prototypes were built? - Development Models	How were prototypes utilized to manage technical risks?
		Testing	- Test Planning - Type of testing - Test environments	To determine if testing follows a structured approach.
		Technology Maturity Measurement tools	- Defined scale - Acceptance criteria	To determine if/how technology maturity was measured? This will also be linked to the reviews under the processes, was the scale applied to make decisions.
		Other methods and tools	- Configuration Management - Speciality Engineering methods.	How were other methods and tools utilized to add value to the process?

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
	TECHNICAL MANAGEMENT **(Linked to RQ 3)**	Planning	- Baselines (Configuration Management) - Management plans - Decision Management - Trial & Error vs structured process - Development phases - Tailoring - Review/Stage gates - Iterations	How the tech development project is planned and managed both technically and as a programme?
		Technical Development Strategy	- Waterfall - Vee - Incremental vs Evolutionary - Spiral - Considerations of technical risk on cost and schedule	To determine the approach and to link this with the development complexity (if possible). Also to investigate tailoring.
		Process Sequencing	- Parallel - Sequential	How was the development process sequenced taking into account the development strategy

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
			-	(uncertainties in development)
		Project Team - Skill levels and mix of disciplines of personnel in Project Development Team.	- Multiple disciplines vs. specialists. - Number of people in a team	SE is a multidisciplinary approach; this is to determine if there are multiple disciplines involved in this project.
		Technology Maturity Assessment	- Maturity assessed? - Levels of assessment (system, sub-systems) - Impact on development process	To determine if technology maturity was assessed and how this impacted the development process.
		Risk Management	- Project Risks - Technical Risks	
	ORGANIZATION AND MANAGEMENT **(Linked to RQ 5)**	Organizational Issues (Impact on the project)	- Alignment of development project to strategy - Organizations special skills (component tech, architectural technologies etc)	Does the project align with the overall strategic objectives of the organization (might be more applicable in a commercial development).

Unit of Analysis	Sub Units of Analysis	Variables	Dimensions to be Considered (For interpretation of data)	Rationale
		Interactions	- Interactions between R&D and product development - Project teams	To establish this interaction and how it fits into the development process.
		Stakeholders	- Internal - External	How do stakeholders fit in to the development process

3.3. Preparation

3.3.1. Case study Protocol

Yin [23] highlights that a case study protocol can be utilized to guide an investigator during data collection. As stated by Yin [23] the case study protocol can have the following elements:

- An overview of the case study project;
- Field procedures;
- Case study questions; and
- A guide for the case study report.

In this research the research proposal and the draft research report contained the necessary information on the research objectives and the key questions prior to data collection. As the author was the main investigator and there was only one site for data collection the case study protocol was informal. A key part of the case study protocol that was used was the field procedures and specifically the following considerations:

- Identification of a nodal point of contact to assist with the data collection.
- A plan to develop the interview questions from research questions.
- Preparation required prior to conducting interviews

During the initial investigations of the case a contact person was identified and the relevant contact details obtained. The contact person was the Lead System Engineer on the telescope segment of the SKA project. All contact for the planning of visits for interviews and for data collection was done via this central contact point.

3.3.2. Interview preparation

The following considerations were made regarding the development of the interview questions and the interview process:

- Type of interview (unstructured, semi-structured or structured);
- Approach to linking the research questions to the interview questions and development of the interview questions;
- Ethical considerations in conducting the interview; and

- Conducting of the interview.

According to Wengraf [27] the research questions cannot be directly asked to interviewees as it is linked to theory or theoretical propositions which may not in a language conducive to interviewing. Wengraf [27] suggests an approach to develop interview questions which link back to the research questions. This is depicted in Figure 3-2. It should be noted that Wengraf [27] uses the term theory question interchangeably with research question.

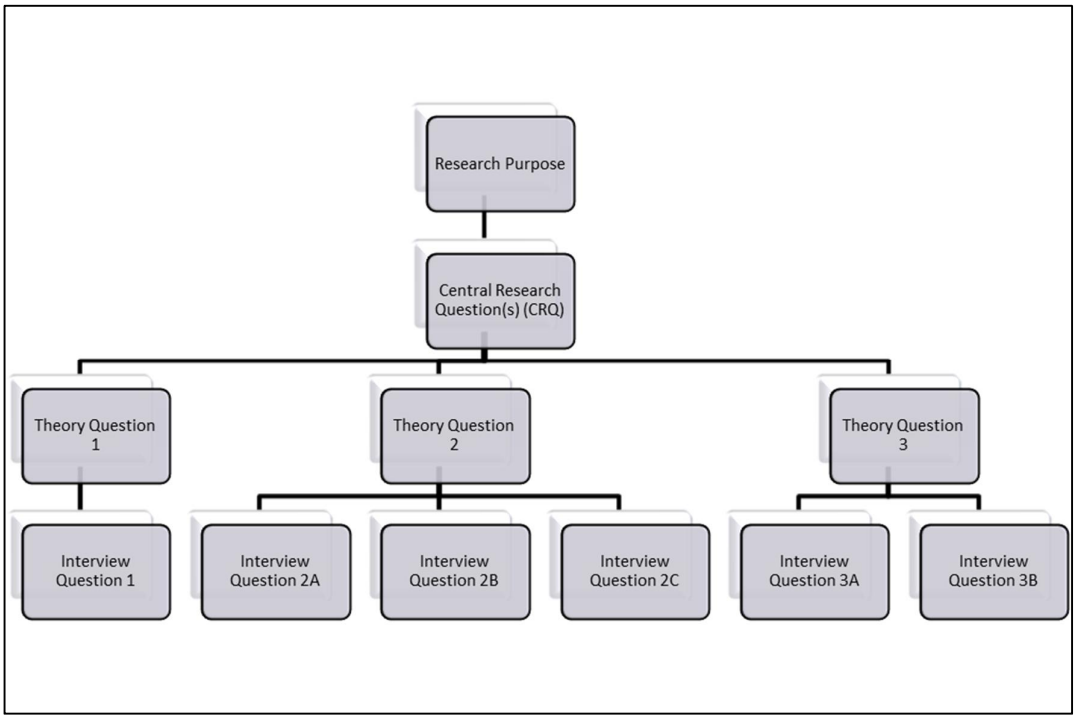


Figure 3-2 Developing Interview Questions from Research Questions [27]

This approach was employed in this research to develop the interview questions from research questions. From the central research question, five sub-research questions were defined in order to provide a linkage to lower level variables which would in turn facilitate the development of interview questions. This process is referred to by Wengraf [27] as instrumenting which is used to obtain useful information out of an interview to answer the theory questions. In this research a semi-structured interview was used with what Wengraf [27] terms “open questions”. Open questions were used in order to elicit a free response to the question and to avoid yes or no type of answers. Prompts were also developed as it difficult to know how the interviewee may answer and the prompt would be used to remind the

interviewer as to the intent of the questions and to adapt during the course of the interview to illicit further information. Due to availability and location of the interviewee (the interviewee was based in Cape Town and the interviewer in Johannesburg) a pilot interview could not be conducted. However after obtaining and doing an initial coding of source documents the interview questions were modified to compliment the documentary evidence and to reinforce it as well (to aid construct validity). Table 3-4 shows the set of interview questions and prompts used to conduct interviews.

Table 3-4 Interview Questions with Prompts

Interview Question	Reference to Theory Question	Question	Prompts
1.	TQ1	What are the most innovative areas in this project?	Components, architecture or application.
2.	TQ1	What were the key challenges facing this project?	In terms of: - Resources (budget and people) - Stakeholders (requirements) - Schedule - Technical - Changing environments
3.	TQ2 /TQ5 (Org &stakeholders)	Were requirements elicited and was there interaction to elicit requirements and from who? Where the stakeholders identified?	Interaction with customers/ key stakeholders?
4.	TQ4 (Technology maturity assessment)	In the SEMP there was no defined way to measure technology maturity? Did this impact decisions to proceed at decision gates?	
5.	TQ4 (Technology maturity assessment)	Did technology maturity influence the project when the full scale engineering and development phase was entered? In what ways?	
6.	TQ3	From the SEMP a Vee type development model was used. Was this tailored further if the development for a given sub-system was more complex?	Tailored to suit the problem situation (eg uncertain requirements, technical difficulties.)
7.	TQ3	What was the planning regarding the project team itself? Was there a mix of disciplines, the roles of the people and how many people were in the team?	

8.	TQ4	Was modelling and simulation (M&S) used during development and for what purposes?	Was M&S used for requirements definition, design, analysis or testing?
9.	TQ4	Was a requirements management tool used in all phases?	Was traceability maintained throughout the project.
10.	TQ5	Did the wider organizational environment promote the undertaking of the project?	Did the organization have appropriate processes? Did the organization provide adequate people and tools?

As highlighted by Wengraf [27] when using open questions the responses are expected to be long thus there does not have to be numerous interview questions. A question such as Question 9 was structured to be less open as it was seeking specific information and as suggested by Wengraf [27] using a closed type of question is more appropriate for specific information.

In order to ensure that the interviewee is protected a consent form was utilized and provided to the interviewee prior to conducting the interview. The consent form included the following statements:

- Participation is voluntary, and the participant may refuse to participate without prejudice;
- The participant may withdraw from the interview at any time without prejudice;
- The participant may decline to answer any question;
- The participant may choose to remain anonymous;
- Any information collected shall be treated as strictly confidential and no individuals will be named in the reporting of the research;
- The interviewer will record (audio recording) the interview for accuracy purposes in transcribing. You may decline to be recorded however it must be noted that this may affect the accuracy of the transcripts made of the interview.

The signed form is in Appendix B of this report. The interviewee did not object to any of the statements and had no issue with being identified as part of the research.

3.4. Data Collection and Approach to Data Analysis

In this investigation a complex development project, conducted under a research and development organization, was used as the case. As stated by Yin [23], one of the means to ensure quality of the case study is to ensure construct validity. The tactic employed during data collection was to use multiple sources of evidence. In order to build a complete description and to see if data converged (during analysis) multiple sources of evidence were used. The case study utilized documents and an interview as sources of evidence.

The documentary evidence can be categorised as project documentation collected from the project office and conference articles authored by personnel that also worked and played a significant role in the technical development of the project. Conference articles were collected as evidence as it provided another perspective of the project to from other individuals involved in the project at the operational level. This provided a lower level view into the detail of the project when compared to the project planning documentation that would provide a high level view on technical management aspects. This additional perspective would also promote construct validity by providing another line of inquiry and would allow the analysis to reveal if the data in the sources of evidence were convergent.

At the early stages of this research when the research questions were developed an initial meeting was held with the Lead System Engineer in order to determine what type of documents could be made available and how the documents could be obtained. During initial meetings, the Lead System Engineer provided presentations that showed an overview of the project. These presentations were the first sources of evidence collected. Further to this the initial meeting was also to investigate willingness to be interviewed and the availability to conduct future interviews which were more structured. Some of the challenges experienced during data collection were the following:

- Access to documentation – The author worked via the Lead System Engineer to obtain documentation and could not have open access to the project documentation. This posed a challenge in terms of which documents could be obtained and also limited the free exploration of documents which could have reveal areas of interest in terms of the research questions.

- Geographical location of the site for data collection – The SKA SA head office was located in Cape Town and the author was based in Pretoria. The distance meant that travel was involved and site visits required preparation in order to get as much done in a short time as possible. The use of email to communicate and send the required documents was utilized as an alternative.
- Document format – The Trade-off analysis report that was received had to be sanitized of pricing and costs. When this was done the pdf document was modified into an image which later impacted its utilization in the data analysis tool.

The following documents were found to be relevant to the case study and were obtained as part of the data collection phase:

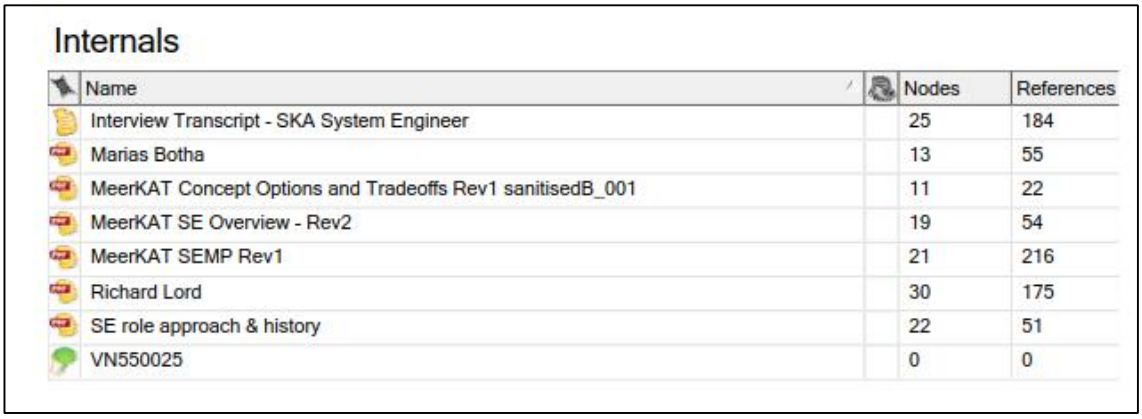
- MeerKat Systems Engineering Management Plan (SEMP) Revision 1
- MeerKat Concept Options and trade-off Report Revision 1
- Systems Engineering Team Roles and Responsibilities (Project Presentation)
- MeerKat Systems Engineering Overview (Project Presentation)
- The Acquisition of KAT 7 (conference article)
- Shaping a Development Strategy based on lessons learnt (conference article)
- Organizational Maturity Development: SKA SA as a case study (conference article)

All documents collected were in electronic format and no hard copies were received which removed any challenge of handling and moving physical documents. The SEMP referenced other documents that were also used as part of project management such as the project management plan and the risk management plan. These documents could not be provided by the system engineering office as the ownership of the documents resided with the project manager.

Another source of evidence that was used for this research was an interview. In arranging and preparing for the interview a brief introduction to the research as well as the questions for the interview was sent to the Lead System Engineer to ensure some familiarity to the topic of interest. There were some practical aspects to the preparation in terms of familiarization of the operation of the recording device and its placement during the interview for best audio quality. Also ensuring a contingency if this audio recording device failed. In order to improve the data collection from the

interview the author practised by interviewing work colleagues to gain some experience with the procedure of conducting an interview. After the actual interview was conducted it was transcribed by the author to allow coding.

Once all the sources of evidence were collected initially simple case study database was formed by creating a folder on a computer. Nvivo Version 10 software, a qualitative data analysis tool, was later used to create a project database as the tool provided an import feature to import sources of evidence as part of the project. Figure 3-3 shows a screen print of the sources database in Nvivo. The Nvivo project file is attached as one of the electronic files in Appendix C of this research report. This is to enable any future study of the case data by an independent investigator.



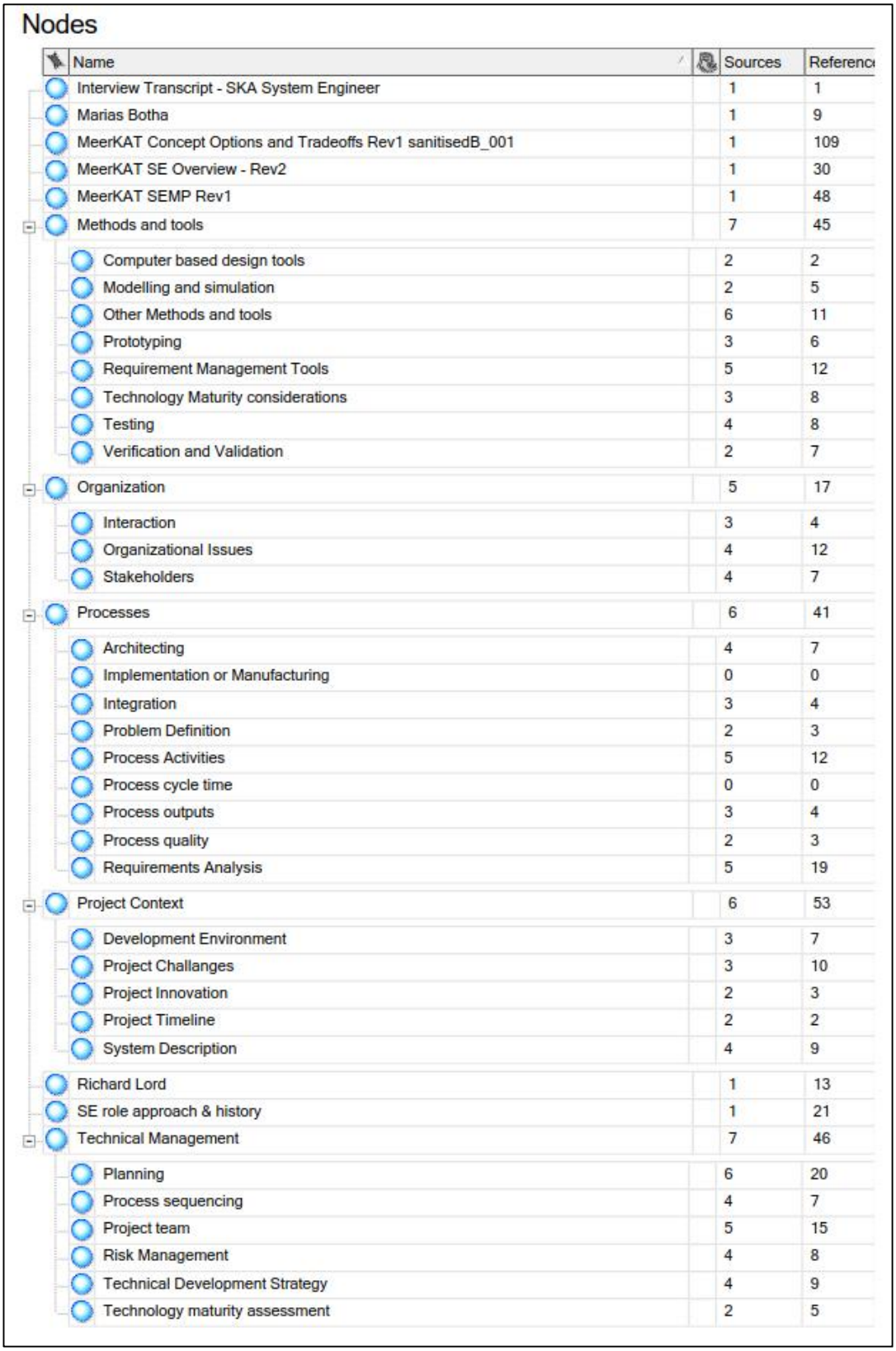
Internals

Name	Nodes	References
Interview Transcript - SKA System Engineer	25	184
Marias Botha	13	55
MeerKAT Concept Options and Tradeoffs Rev1 sanitisedB_001	11	22
MeerKAT SE Overview - Rev2	19	54
MeerKAT SEMP Rev1	21	216
Richard Lord	30	175
SE role approach & history	22	51
VN550025	0	0

Figure 3-3 Case Study Source Databse

The coding features of the Nvivo software were used to create themes in line with the sub units of analysis (theme nodes) and variables (child nodes) of the case study. Each source was coded at each theme using the considerations defined in Table 3-3. Words, phrases, paragraphs and images from the sources were all coded if it was in line with the variables and concepts identified in Table 3-3.

The first five nodes in Figure 3-4 are not theme nodes but are case nodes defined in order to do data queries which will be illustrated in the results and discussion section. The sources and references columns each respectively show the number of sources and the number of times that particular theme node was coded in the data. The nodes were structured in this manner to logically enable the data coded in the sources to be linked back to the unit of analysis and the sub units of analysis in order to address the research questions.



Nodes

Name	Sources	Reference
Interview Transcript - SKA System Engineer	1	1
Marias Botha	1	9
MeerKAT Concept Options and Tradeoffs Rev1 sanitisedB_001	1	109
MeerKAT SE Overview - Rev2	1	30
MeerKAT SEMP Rev1	1	48
Methods and tools	7	45
Computer based design tools	2	2
Modelling and simulation	2	5
Other Methods and tools	6	11
Prototyping	3	6
Requirement Management Tools	5	12
Technology Maturity considerations	3	8
Testing	4	8
Verification and Validation	2	7
Organization	5	17
Interaction	3	4
Organizational Issues	4	12
Stakeholders	4	7
Processes	6	41
Architecting	4	7
Implementation or Manufacturing	0	0
Integration	3	4
Problem Definition	2	3
Process Activities	5	12
Process cycle time	0	0
Process outputs	3	4
Process quality	2	3
Requirements Analysis	5	19
Project Context	6	53
Development Environment	3	7
Project Challanges	3	10
Project Innovation	2	3
Project Timeline	2	2
System Description	4	9
Richard Lord	1	13
SE role approach & history	1	21
Technical Management	7	46
Planning	6	20
Process sequencing	4	7
Project team	5	15
Risk Management	4	8
Technical Development Strategy	4	9
Technology maturity assessment	2	5

Figure 3-4 Theme Nodes used for Coding of Case Study Data

The Nvivo tool has an automated reporting feature that can generate a report for which extracts and summarizes the coded source data, across all sources, for each theme node. This report facilitates quick reference to the coding and provides a way to see any relationship of the theme between the various sources. This assists with internal validity as the convergence (or divergence) of the sources of the data can be seen. This report was useful especially when analysing the data in order to answer the research questions. The process of coding could be carried out in different ways using the Nvivo tool such as using performing a text search and coding as one proceeds through a source. However defining the theme nodes and then coding with them provides a more directed approach to analysing the evidence.

The interpretation and discussion of the data will be presented in the results and discussion section of the document. However, in order gain a better appreciation of the analysis the case study will be introduced in the next section.

3.5. Summary of Reliability and Validity

Table 3-5 by Yin [23] shows tactics to be considered to ensure validity and reliability when undertaking case study research.

Table 3-5: Tactics to Ensure Research Validity [23]

TESTS	CASE STUDY TACTIC	PHASE OF RESEARCH IN WHICH TACTIC OCCURS
CONSTRUCT VALIDITY	· Use multiple sources of evidence · Establish chain of evidence · Have key informants review draft report	· Data collection · Data collection · composition
INTERNAL VALIDITY	· Pattern matching · Explanation building · Address rival explanations · Use logic models	· Data analysis · Data analysis · Data analysis · Data analysis
EXTERNAL VALIDITY	· Use theory in single-case studies · Use replication logic in multiple-case studies	· Research design · Research design

RELIABILITY	· Use case study protocol · Develop case study database	· Data collection · Data collection

In light of the points presented in Table 3-5, a summary of the approach used in this research to ensure validity and reliability is highlighted in this section.

- To ensure construct validity project documentation, conference articles and an interview were utilized as multiple sources of evidence for the case study.
- To ensure internal validity, Toulmin's model of argumentation [30] was used as a logic model to structure any claims made from the data analysis. This is further explained in Section 5.1 of this report.
- To ensure external validity, theory extracted during the literature review was utilized as warrants when presenting the results. This is presented in Sections 5.2 to 5.7 of this report.
- To ensure reliability, the approach stated in Sections 3.3 and 3.4 were used to collect data. A case study database was also established, using the Nvivo 10 software tool, as presented in Section 3.4.

4. CASE STUDY INTRODUCTION – SQUARE KILOMETER ARRAY (SKA) PROJECT

4.1. Square Kilometre Array Project

The Square Kilometre Array (SKA) is an array of radio telescopes that will have a collecting area of one square kilometre. A radio telescope collects radio waves emitted from objects and uses signal processing to form an image from the radio waves. Before the actual Square Kilometre Array is built there are 2 pre-cursor projects that are being undertaken. KAT-7 is an engineering prototype for the MeerKAT array. The MeerKAT array, which is currently under development, has started being constructed in the Karoo. MeerKAT will consist of approximately 64 dishes. A rendition of the type of dish that will be used is shown in Figure 4-1.



Figure 4-1: Rendition of a MeerKAT Dish (Image Credit: SKA South Africa)[27]

4.1.1. Selection of SKA South Africa Telescope Development as a Case Study

The SKA project is an unprecedented project in South Africa. The system to be developed is not available commercially off-the-shelf and has to be designed and developed from scratch which makes it an ideal project for investigating the

development process. The detailed considerations for selecting this as a case study are as follows:

- The Development Environment – The SKA and MeerKAT are tools that will primarily be developed to be used by the radio astronomy scientific community. The key stakeholders are the astronomy science users from the local and international community. This development makes it applicable to an investigation of a development in the research and development environment.

- Technical considerations – The design and construction of the dishes as well as the surrounding infrastructure such as the data processing and data storage technology make this a highly technical undertaking. The fact that some of the technology is still being matured means that there is considerable technical risk. A system breakdown structure for the system is shown in figure 8 to illustrate the system levels and the various sub-systems. Each of the system elements as illustrated in Figure 4-2 are systems on their own which makes the entire MeerKAT system a complicated system which has many levels. This shows that the systems are highly complicated as there are multiple sub-systems that integrate together. Further to this there are multiple disciplines of engineering required such as the mechanical engineering for structures, electronics engineering for the radio frequency sub-systems and software engineering for data processing software. Taking into consideration the multiple disciplines required as well as the development and operating environments of the project, it is seen that this is a highly complex project.

- Scale of the development – The MeerKAT array will consist of approximately 64 dishes spread over a large area in the Karoo and the SKA approximately 3000 dishes spread over a large geographical area in Southern Africa and Indian Ocean Islands. The project is led by a research and development organization being the National Research Foundation (NRF) and a project of this scale is usually not associated with a R&D undertaking. This aspect also makes the case

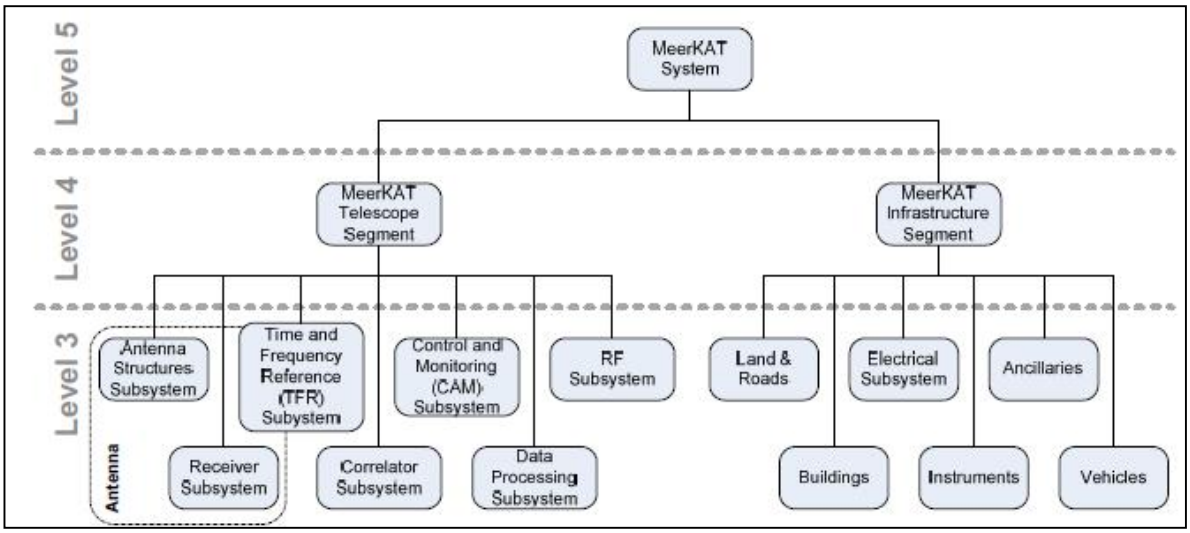


Figure 4-2: MeerKAT System Breakdown Structure (Credit: SKA South Africa) [29]

- Application of Systems Engineering to the Project – A systems engineering approach was applied in this project from the start of execution of the project which is evident in the System Engineering Management Plan. The central research question of this research is to study the role of systems engineering in an R&D project and how uncertainties and associated risks are managed in this context. Thus, the case is considered a critical case study to address the central research question.

5. RESULTS AND DISCUSSION

5.1. Structure of the Results and Discussion

In order to present the evidence to answer the research questions in a logical manner the results and discussion is structured as follows:

- The coding of the evidence is structured in accordance with the research questions and themes around the questions as described in section 3.4. Each section in the research and discussion is presented to address a research question which will conclude with discussing the central research question.
- In each section statements will be made and key evidence will be presented to answer the research question. In order to put forward a logical and substantiated explanation, Toulmin's [30] model of argumentation will be used and the approach is elaborated on before proceeding to the results and discussion.
- The coding process using Nvivo 10 yielded a large amount of data extracted from the various sources as illustrated in Table 5-1. The columns in Table 5-1 show the various sources of data and the rows show the theme nodes at for the case. The numbers at the intersection of the source data and theme node represent the number of codes done in that source for that particular theme node. Thus the key evidence from the coding will be extracted and highlighted when needed to support an argument. The full coding summary report is attached an electronic file as part of Appendix C.

Table 5-1 Summary of Coding references for each node for each source

	A : Conference article:Presenter Role = System Engineer/ Project Manager	B : Conference article:Presenter Role = Engineer	C : Person:Occupation = Lead System Engineer	D : Project documentation:Document Type = Management Plan	E : Project documentation:Document Type = Presentation	F : Project documentation:Document Type = Report
1 : Methods and tools	12	6	7	12	4	4
2 : Computer based design tools	0	0	1	1	0	0
3 : Modelling and simulation	2	0	3	0	0	0
4 : Other Methods and tools	1	0	1	5	2	2
5 : Prototyping	2	3	1	0	0	0
6 : Requirement Management Tools	2	0	3	4	1	2
7 : Technology Maturity considerations	1	3	4	0	0	0
8 : Testing	5	0	1	1	1	0
9 : Verification and Validation	5	0	0	2	0	0
10 : Organization	6	0	7	0	3	1
11 : Interaction	1	0	2	0	1	0
12 : Organizational Issues	4	0	5	0	3	0
13 : Stakeholders	2	0	3	0	1	1
14 : Processes	10	0	5	9	13	4
15 : Architecting	1	0	0	3	1	2
16 : Implementation or Manufacturing	0	0	0	0	0	0
17 : Integration	2	0	0	1	1	0
18 : Problem Definition	2	0	0	0	1	0
19 : Process Activities	2	0	0	1	8	1
20 : Process cycle time	0	0	0	0	0	0
21 : Process outputs	0	0	0	2	2	0
22 : Process quality	0	0	0	0	3	0
23 : Requirements Analysis	5	0	4	6	1	3
24 : Project Context	8	5	5	3	5	0
25 : Development Environment	3	0	1	0	3	0
26 : Project Challanges	6	1	3	0	0	0
27 : Project Innovation	0	1	2	0	0	0
28 : Project Timeline	0	0	0	0	2	0
29 : System Description	1	4	0	3	1	0
30 : Technical Management	10	4	7	6	18	1
31 : Planning	2	1	1	8	8	0
32 : Process sequencing	1	0	0	1	5	0
33 : Project team	3	0	3	1	8	0
34 : Risk Management	3	3	0	0	1	1
35 : Technical Development Strategy	4	2	0	0	3	0
36 : Technology maturity assessment	0	1	4	0	0	0

Toulmin's model of Argumentation also referred to as Toulmin's Logic Model by Friedman and Sage [24] is a way in which to present a case study analysis. The model consists of the elements in Table 5-2 as defined by Karbach [30].

In the discussion, a claim will be made to address the research question and evidence (the grounds) from the coded sources will be presented to substantiate the claim. The warrants for the claims are the theoretical propositions or hypotheses presented which are taken as generally accepted as they are based on the literature (backing). Any rebuttal or qualifier that can be identified will be stated. As stated by Karbach [30] the essential aspects for a successful argument are the claim, grounds and warrant. The model in diagrammatic form is shown in Figure 5-1.

Table 5-2 Elements of Toulmin's Model of Argumentation [30]

ELEMENT	DEFINITION
CLAIM	The basic purpose of an argument (assertion, standard or thesis)
GROUNDS	The foundation of the argument (evidence or specific facts that support the claim)
WARRANT	Links the grounds to the claim and gives the grounds general support (applicability to the claim)
BACKING	Establishes the reliability and relevance of the warrant.
REBUTTAL	Acknowledges exceptions that might invalidate the claim.
QUALIFIER	Modifies the claim – limits the strength of the argument or proposes the conditions under which the argument is true.

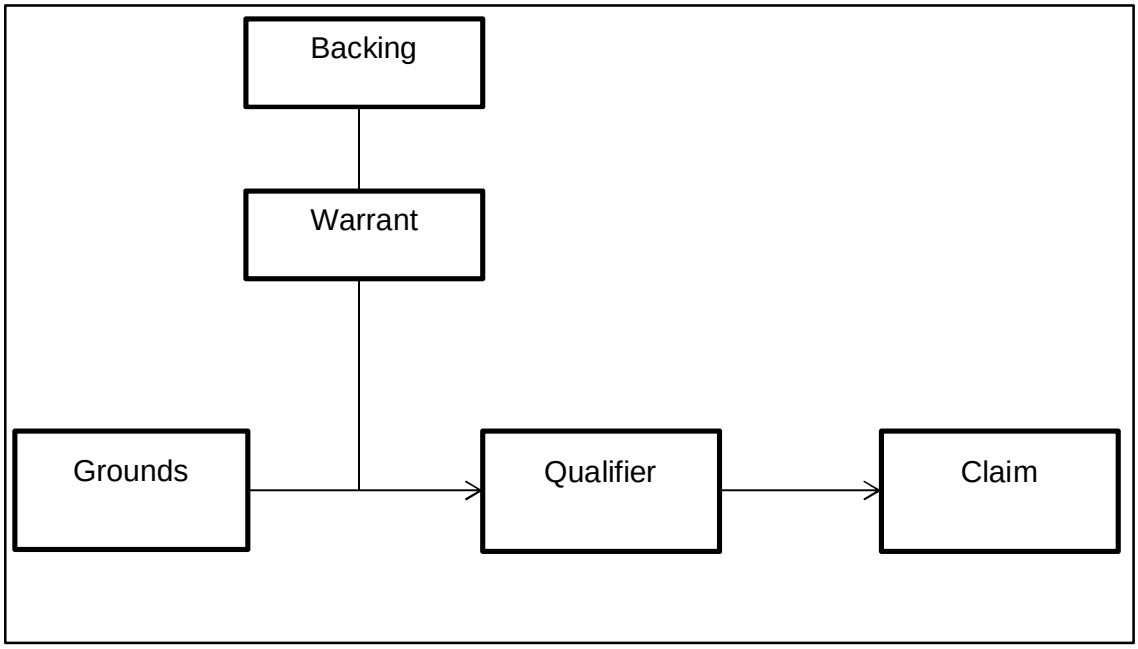


Figure 5-1: Toulmin's Model of Argumentation [30]

5.2. How suitable is a systems engineering approach to a Research and Development Project? (RQ1)

Systems engineering has been typically applied to large scale, complex product development projects. This research question was defined to investigate the applicability of a systems engineering approach to a project undertaken in a research and development environment.

The development environment for the SKA project is characterised by the following:

- A complex system requiring multiple engineering disciplines.
- A demanding operating environment.
- High technical uncertainty due to lack of experience with radio astronomy by the design team.
- Expertise and capability in special technology for radio astronomy such as radio frequency (RF) electronic equipment and cryogenic cooling.

The system breakdown for the MeerKat development of the SKA Project is depicted in Figure 4-2. This evidence supports the claim that the system is complex as it can be seen in the figure that there are multiple sub-systems. Furthermore the system breakdown also considers the enabling environment in terms of road infrastructure electricity and the other aspects. The inclusion of the infrastructure segment shows

that the system as a whole had to be considered. This holistic type of consideration shows a systems thinking approach.

The system breakdown also shows that each sub-system is different for instance there is an antenna structure, RF and data processing sub-systems. Each of these sub-systems requires a different engineering discipline to develop them. A multi-disciplinary project team had to be used in order to successfully carry out the SKA project. An extract from the interview conducted also supports this, (Appendix B ref 045)

"*we have a wide range of different technologies from infrastructure to mechanical, to RF electronics, digital electronics and software. So we had to look at each of those disciplines and see what the best way to get that technology up and running as quickly as possible. For each different technology it worked out slightly differently so for some of them, like for software we decided to do everything in house, we decided we can get good software people and get them up and running quite quickly. For some sub-systems like the dish structures, the mechanical systems we decided to contract that out to an industry player because it would be difficult to build up that capability in a short period of time*."

The operating environment also had to be considered in the development of the system and for successfully operating the system. This shows that the system life-cycle consideration was applicable in development of the system. The system life-cycle is again linked to systems thinking and the holistic approach of system engineering. Specific evidence of this is shown in Figure 5-2 which shows the development process followed in this project.

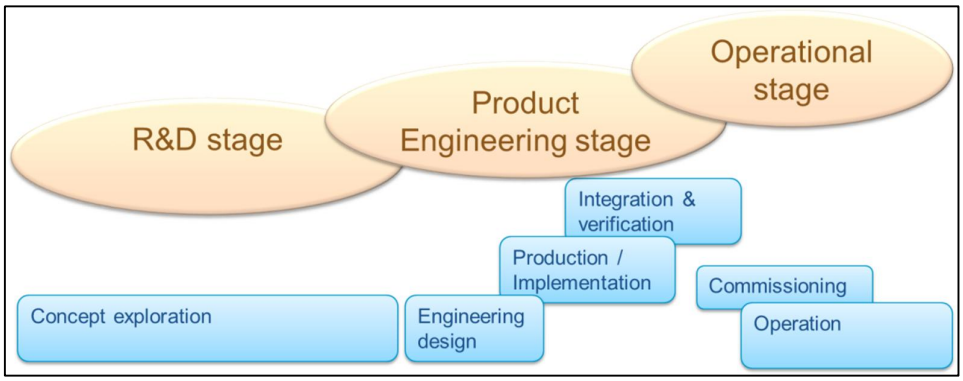


Figure 5-2: SKA South Africa Development Process [27] (Credit: SKA South Africa)

In the operational stage evidence of operational considerations of the system are, as stated in the paper by Lord [31], that the support during operations of the KAT-7 was developed during the acquisition stages with the use of a logistic engineering management plan. Further to this Lord [31] also states that an Operational Concept Description was used to plan the telescope operations.

"*Another important document at the time was the Operational Concept Description (OCD), which had the following main objectives:*

• *Elicit requirements for the KAT-7 Telescope;*

• *Serve as a high-level plan for the KAT-7 Telescope operations*".

Evidence of operating environment considerations was also found in the paper presented by Lord [31] (also see Appendix C Node Report page 45).

"*Challenging Karoo environment. Any system erected in the Karoo must be able to withstand dust, strong winds, lightning, and large variations in temperature.*"

The development and the operating environment had high technical uncertainty as there was no existing development organization and the team was inexperienced with radio astronomy and designing, building and operating radio telescopes. Evidence of this was found in both the interview transcript and the paper presented by Lord [31] respectively shown in the extracts below,

"…*because we started this project from scratch without any people so we had to grow the organization along with growing the "technology and growing the processes." (Appendix C page 45)*

"*Lack of user domain experience. The Systems Engineering team had little experience in radio astronomy and in building radio telescopes.*" [31]

In order to address this technical uncertainty a risk reduction approach was followed to grow project team capability as well as incrementally develop the MeerKat radio telescope by utilizing less complex development models. This is shown in Figure 5-3.

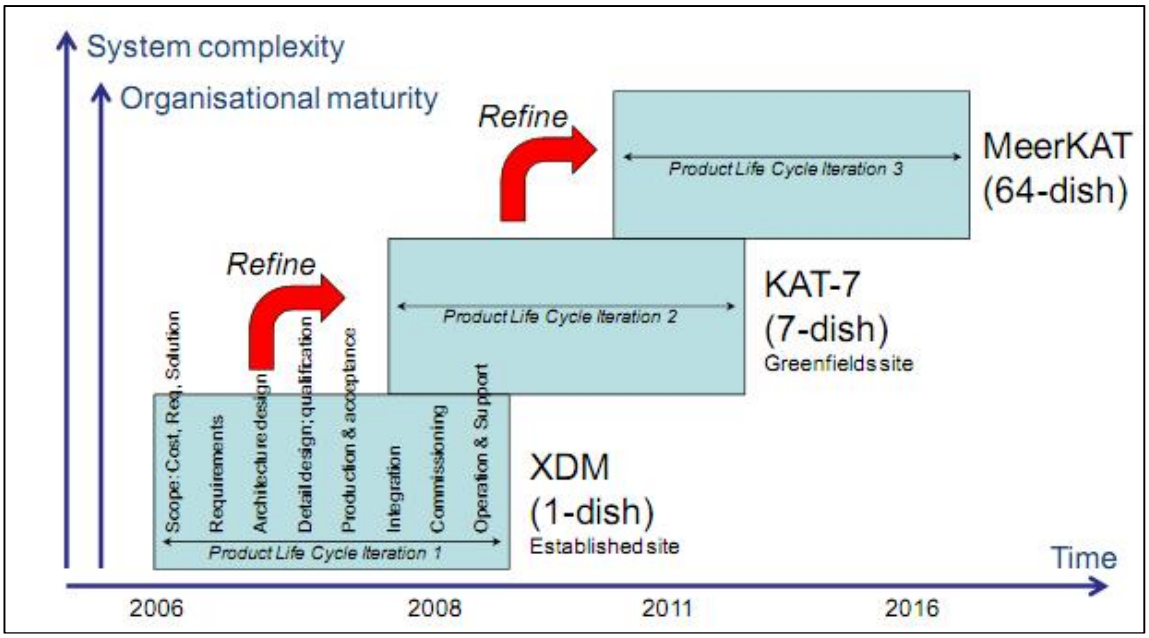


Figure 5-3: Risk Reduction Approach in System Development Process (Credit: SKA South Africa) [27]

As stated in the INCOSE Handbook [3], a primary goal of a system engineer is to reduce risks. In order to address (RQ1), the evidence presented above is to support the claim that systems engineering is applicable to the research and development environment particularly a complex project in the technology development part of the R&D spectrum. The evidence shows that in the project the system under development in its environment was complex and the technical risks were high from the inception of the project due to lack of experience with radio telescopes. A system

engineering approach was utilized to reduce risks by using development models as shown in Figure 5-3. Without utilizing a risk reduction approach the risks would not have reduced. Risk reduction came about as experience with radio telescope development and operation was gained by the team incrementally with each successive development model over time.

The management of a multidisciplinary team as part of the project is also an aspect of systems engineering management. The high technical risks present in the project as shown in the case also make systems engineering technical management applicable. These considerations make the systems engineering approach applicable to the environment as shown in the case. As presented in the literature review section, these conditions also exist in general in other R&D projects.

A qualifier to this claim however is that the project undertaken in this case falls more in the applied research and technology development end of the R&D spectrum. In terms of the TRL levels shown in Figure 2-4 this represents a TRL 5 or greater. The pure research aspects were not considered and the applicability of SE in that context was not investigated.

To summarize, Figure 5-4 shows the considerations of the Toulmin model of argumentation applied to RQ1.

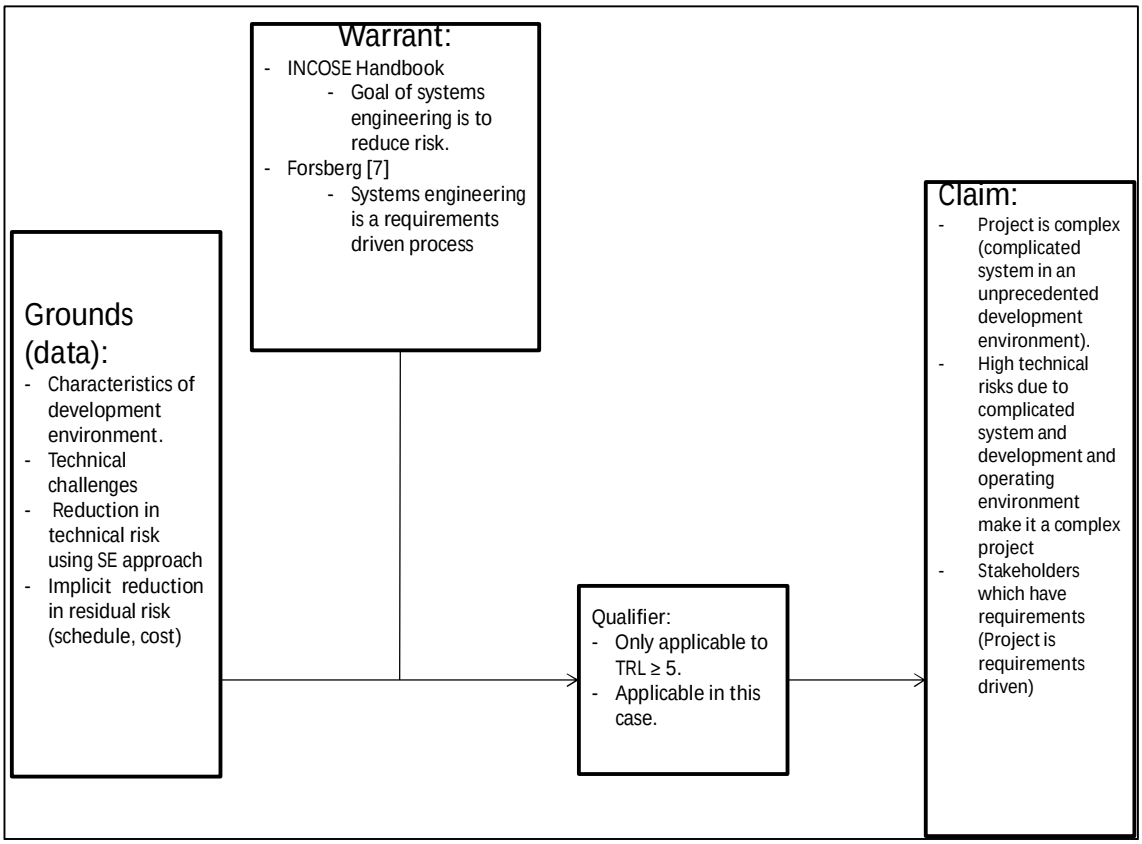


Figure 5-4: Toulmin model applicable to RQ 1

5.3. How is the development process structured in the project and why? (RQ2)

The purpose of RQ 2 is to focus on the technical process (activities) used in executing the project.

The overview of the project plan which shows the technical processes is shown in Figure 5-5.

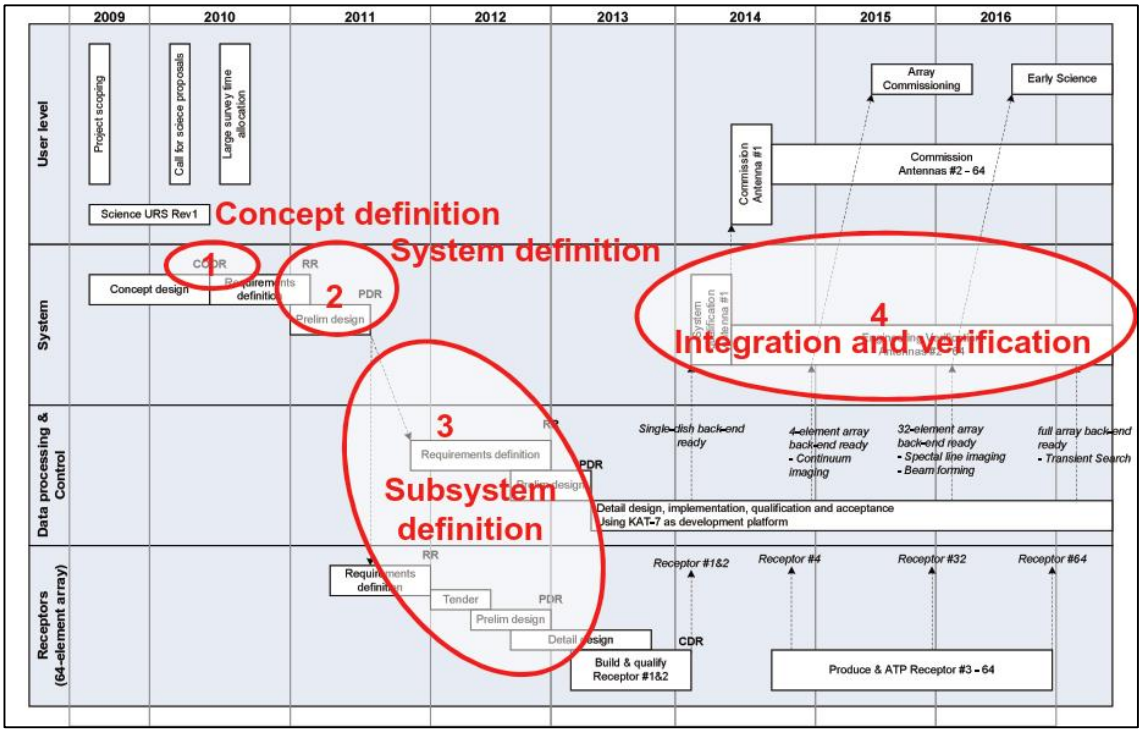


Figure 5-5 Project Plan Overview [33]

In addition to this the Systems Engineering Management Plan (SEMP) [29] lists the following together with a brief extract of the purpose as quoted from the SEMP:

Table 5-3 Definition of Technical Stages in the SKA Project

ACTIVITY DESCRIPTION	**PURPOSE (As extracted from the SEMP)**
Concept Definition	*The purpose of concept definition is to identify one or more architecture options which will satisfy the requirements and to trade off these options to decide on a preferred architecture, which can then be developed in more detail.*
Requirements Definition	*The purpose of this stage is to define the "problem" (WHAT is required). The aim is to capture and validate a complete, unambiguous and traceable set of requirements for an item, so that there is no misunderstanding between different stakeholders as to what is required.*

Preliminary Design	*The purpose of the preliminary design stage is to define the "solution" (HOW will the requirements be achieved)*
Detail Design and Qualification	*The purpose of the detail design stage is:* *a) To define the complete design down to component level, which can be produced/implemented/procured.* *b) To qualify that the design will meet all requirements.*
Implementation	*The purpose of this stage is to produce/build, test, install and accept an integrated item. This stage includes implementation, integration, integration testing and acceptance testing.*
Production	*The purpose of this stage is to produce, test and accept an integrated item. This stage includes production, assembly, integration testing and acceptance testing.*

The claim to address RQ 2 is that the process or stages as shown are structured to take a complete set of stakeholder requirements and to realise a physical entity that would meet those requirements. This while addressing the risks (budget, cost and performance) at reviews which takes place between the stages. This is evident in the purposes of the stages above as well as the sequencing of the stages as will be elaborated.

With each stage the process takes the requirements from a more conceptual form to actually realizing a physical entity that will meet the defined requirements by performing verification activities (integration testing and acceptance testing). The concept definition stage utilized high level user requirements as inputs (science requirements) in order to select architecture from a range of options taking into account capability and feasibility. The output of this stage is a concept design document which captures the preferred architecture option and the rationale for the selection (see Appendix C page 30 for full evidence). Lord [31] also highlights that a

document utilized during this stage was an operational concept description which was utilized to elicit requirements for the KAT-7 telescope and as a high level plan for the operations of the KAT-7 telescope (which later formed the basis for MeerKat).

In between each stage is a design review to address risks in terms of cost, schedule and technical capability (the details of the review will be presented under the technical management part of the discussion). Even though the stages are stated in a particular order they are not necessarily executed that way. Evidence of this is in Figure 5-5 which shows that at the sub-system level the stages can run in parallel for different sub-systems.

Requirements definition focuses on the system requirements which flow down from the user requirements. As the systems engineering process is requirements driven the requirements definition is a key process. The user requirements were elicited from proposals as stated in the interview transcript (Appendix B and Appendix C Node report page 37):

"*We asked for proposals for science for scientists to use it. They generated proposals and that created a very clear set of stakeholders so those key science projects are our stakeholders and we elicited all the requirements through them and checked everything with them, the user requirements.*"

A requirements analysis method (to be discussed in section 5.5 of the discussion) was followed to define the requirements, check for completeness and ensure they are verifiable. The output of this stage is a requirements specification which is an input to the design stages. It was stated in the SEMP that the requirements definition and architecture definition were done concurrently in order to capture requirements revealed through design process.

As stated in the end of section 2.2.2 one of the top 10 contributors to projects failing is incomplete requirements. The application of the requirements definition process is to ensure complete requirements. As highlighted in section 2.2.2 application of SE early in the design process reduces technical risk by avoiding requirements and design changes which can negatively impact cost and schedule.

The Preliminary Design stage was utilized to define the solution. A functional and physical architecture of the system were defined using an architecting method described in the SEMP,

"*This method describes a structured and iterative approach for designing a complete and coherent functional and physical architecture, while ensuring that all requirements are met. This process typically results in multiple possible architectures, each with its advantages and disadvantages. In such cases a trade-off study shall be performed to decide which of the alternative solutions will best meet the requirements.*" [29]

The system design was also described in the Role and SE Presentation as follows:

"*Interpreting user requirements and translating them to system spec. Designing the system architecture and deriving subsystem specs.*" [27]

Trade-off studies were also utilized to select the best architecture considering requirements, schedule and cost. Evidence of this is an example of trade-off summary for the antenna structure as extracted from the trade-off study report is shown in Figure 5-6 (note cost not shown and blocked out by the project official).

Table 10: Cost, risk and schedule comparison for Antenna options considered

Antenna option	Total Cost (x1000)	Technical risk	Schedule
Baseline option	R	**Low**	**Mid 2014**
Option 1 (KAT7 improved)	R	**Low**	**Mid 2014**
Option 2 (Prime focus 13.5m)	R	**Low**	**Mid 2014**
Option 3 (Offset Gregorian 12m)	R	**High**	**Mid 2015**
Option 4 (Offset Gregorian 13.5m)	R	**High**	**Early 2015**
Option 5 (Prime focus 14.7m)	R	**Low**	**Mid 2014**

Figure 5-6 Example of Trade-off Summary for Antenna Structure [34]

The Detailed Design and Qualification stages were utilized to complete the design for lower level components and to do qualification on the item using testing in a simulated environment. Figure 5-7 shows that the system requirements feed into sub-system requirements until the lowest level is reached. The qualification then follows up from this with bottom up verification, integration up to system level.

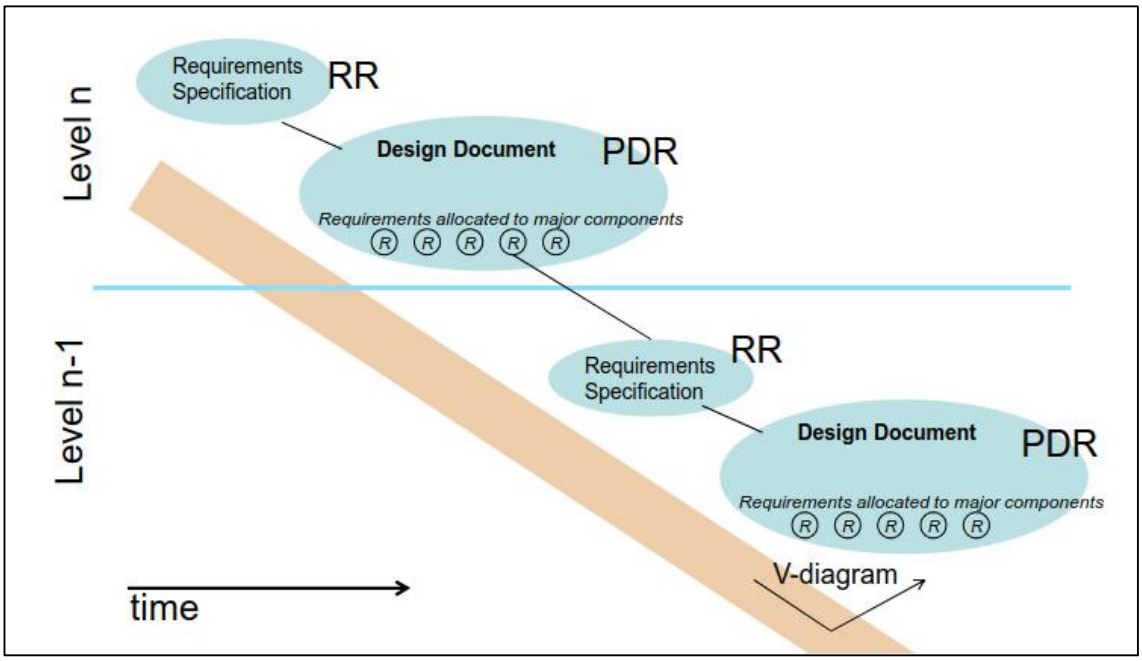


Figure 5-7 Detailed Design Process in General [33]

Utilizing the flow-down of requirements from the highest level to the lowest level ensures traceability which ensures the requirements are complete and that there are no extraneous requirements. As highlighted in the INCOSE Handbook [3] every requirement has a cost associated with it in order to meet it.

Qualification was used to verify that the design would meet all of the requirements. The evidence extracted from the SEMP and the paper by Lord [31] state respectively,

"*Qualification is performed on the detailed design by providing evidence to justify that the design meets all requirements*" [29]

In section 5.5 of the discussion evidence is shown of the use of modelling and simulation as a tool to verify requirements.

"*At SKA South Africa, qualification testing is performed on all items. The qualification test procedure (QTP) verifies that the end-to-end design meets the given requirements*." [31]

The implementation and production stages are utilized to physically build the designed items and to assemble and integrate them until the complete system is built. The bottom up verification as the system is integrated is used to reveal the

emergent properties of the system (both wanted and unwanted). The structure of top down design and bottom up implementation and verification is shown in Figure 5-8.

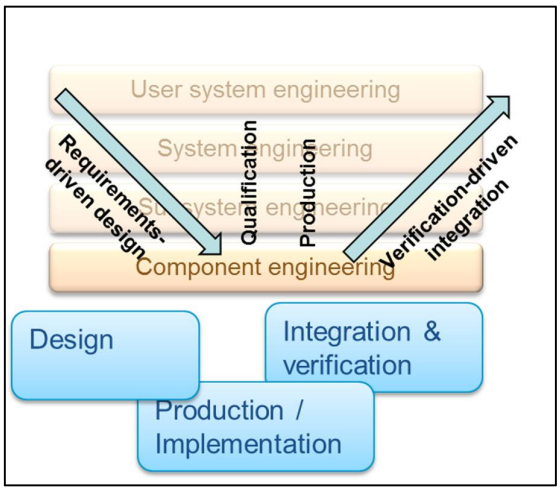


Figure 5-8 Structure of Design, Implementation and Integration and Verification Stages [27]

The stages utilized are comparable to the technical processes as described in the INCOSE Handbook [3] but are not exactly the same. However the purpose of the processes used in the SKA project as described above match that described in the INCOSE Handbook [3] which is,

"*creation of a sufficient set of requirements and resulting system solutions that address the desired capabilities within the bounds of performance, environment, external interfaces, and design constraints. Without the technical processes, the risk of project failure would be unacceptably high.*" [3]

Use of a traditional engineering design approach could result in a system that would work but may not necessarily meet all the user requirements. Application of SE technical processes ensures that a complete and verifiable set of user and system requirements can be achieved. This positively impacts the cost and schedule by avoiding additional costs and usage of time to do design changes due to incomplete requirements or changing requirements.

A qualification to the claim is that the application of the technical processes still requires expertise in the various disciplines in order to translate the higher level requirements into design requirements and to define the appropriate verification

requirements. Simply following the processes does not mean a successful system will be realized.

In the definition of the design only mature technologies were considered (this will be elaborated in section 5.4 of the discussion) as highlighted in the SEMP. Therefore another qualification to this claim is that only TRL levels of 5 and greater can be considered applicable as the development utilized technology that was integrated at a laboratory level and then tested in laboratory or simulated environment for qualification.

The Toulmin model applied to RQ 2 is shown in Figure 5-9.

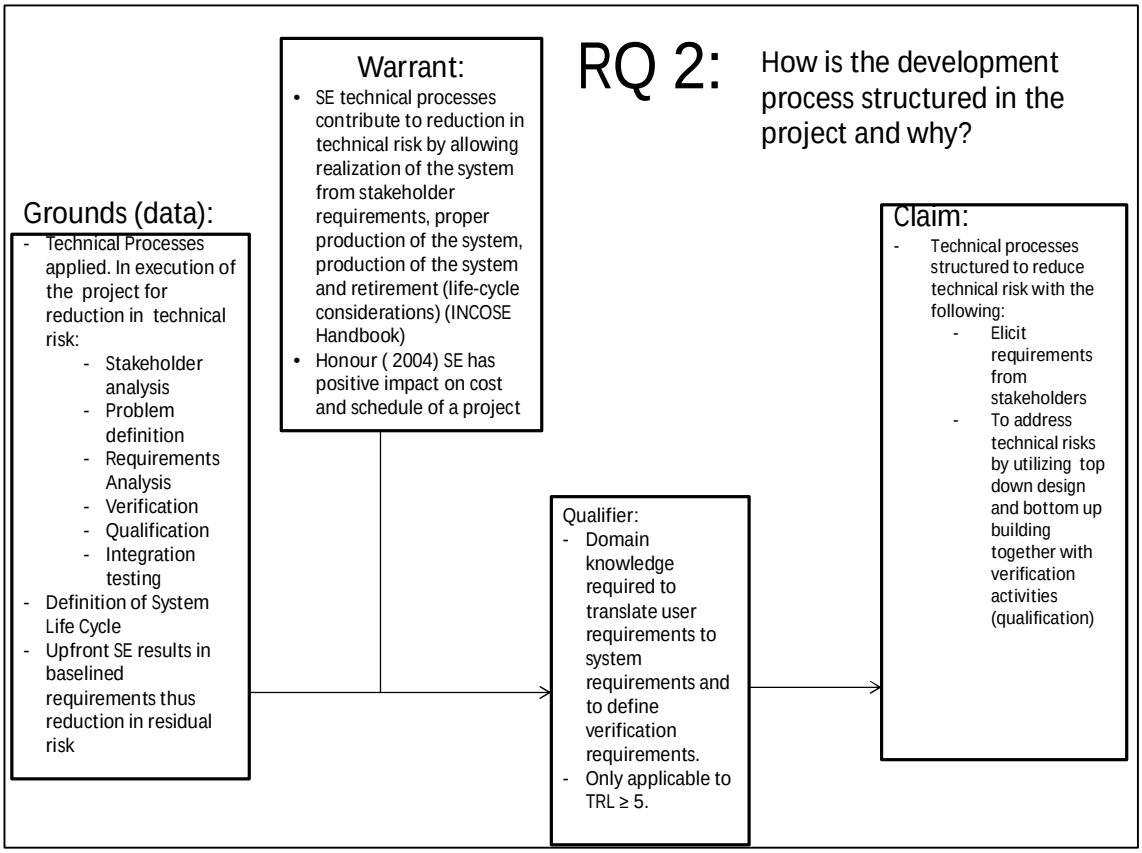


Figure 5-9 Toulmin model applicable to RQ 2

5.4. How is the technical development process and associated risks managed? (RQ 3)

The focus of RQ 3 is to investigate the planning of the development process in order to manage customer, cost, schedule and technical risks.

The claim to address this question is that the reviews were utilized as control gates to assess cost, schedule and technical risks and as decision points. The use of baselines were also utilized in order to formally manage change control and as a firm reference point from which to continue with development.

The following will be highlighted in this section as evidence of this:

- The use of baselines and reviews
- Project team responsibilities
- Risk management
- Development Strategy
- The use of development models
- Technology maturity considerations

The planning of the baselines and reviews in relation to the stages is shown in Figure 5-10. This extract of the planning is taken from the SEMP for the telescope segment.

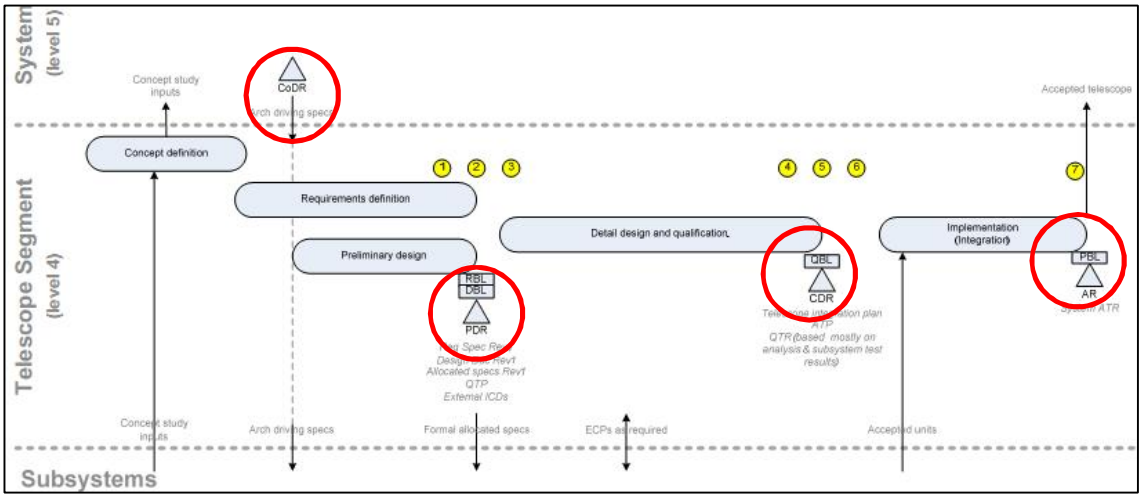


Figure 5-10: Baselines and Reviews for a Sub-system of the SKA Project [29]

The red rings highlight the points and show the review which takes place and the baseline to be established at that point. In the SEMP the outputs of each stage are

described in detail and these form the basis of the respective baseline for that stage and is explicitly stated at which review this baseline will be established. An example of this as extracted from the SEMP as quoted below.

"*The output of the concept definition phase is a concept design document, which captures the architecture tradeoffs, a chosen architecture, with rationale for the choice, and traceability to requirements. The concept is reviewed formally in the Concept Design Review (CoDR). For the system (level 5), the CoDR can only be closed after the user requirements baseline has been established and after the concept (with associated time and budget implications) has been approved by the steering committee.*" [29]

The definition of the reviews is also stated in the SEMP and clearly shows the purpose of the review and the requirements of the review. The definition of the concept design review is used as an example, which is extracted from the SEMP as shown below:

"*The purpose of the concept design review is to ensure that there is agreement among stakeholders that:*

a) All architecture driving requirements are understood.

b) A suitable set of architecture design concepts have been explored and traded off.

c) An "Option A" architecture concept is chosen which will be developed in detail in the preliminary design stage.

The following documents shall form part of a concept design review:

a) Approved higher-level requirements allocated to the item.

b) Concept Design Document, which shall contain the following:

i. Derived architecture driving requirements for the item.

ii. Architecture design options and tradeoffs.

iii. Rationale for chosen option.

iv. High level architecture description for the chosen option.

v. Architecture driving lower-level requirements." [29]

Continuing to use the concept stage as an example the risks are addressed by considering the key architecture driving requirements which are linked to a performance measure. From the Concept Options and Trade-off's design document (which is an output of the Concept Stage and a document used to establish the Requirements Baseline or RBL) and utilizing the pointing accuracy as a key design parameter in Figure 5-11.

Option	Risk of not achieving 15arcsec RMS pointing accuracy requirement	Comment	Mitigation
Base option (KAT-7, 12m)	Low	Demonstrated	Risk manageable as part of design process
Option 1(KAT - 7 improved, 12m)	Low	Improvements identified, cost of reduction must be understood.	Risk manageable as part of design process
Option 2 (Prime focus 13.5m)	Low	Effect of increased size must be understood but risk considered low	Risk manageable as part of design process
Option 3 (Offset Gregorian 12m)	High	Interaction of deflections could be cumulative under certain load conditions and combinations of load conditions. A wide range of load combinations have to be investigated to understand the impact.	Perform load case analysis and numerous simulations runs to understand cross coupling effects of deflections that impact pointing accuracy over the entire range of intended operation of the telescope. This activity will consume a large engineering/analysis effort
Option 4 (Offset Gregorian 13.5m)	High	Same as above	Same as above
Option 5 (Prime focus 14.7m)	Low	Effect of increased size must be understood but risk considered low	Risk manageable as part of design process

Figure 5-11 Extract of Risk Assessment in Concept Design Document [34]

Figure 5-11 shows the consideration of the impact of different antenna architecture on pointing accuracy performance. This is essentially management of a technical risk. Cost and schedule implications are also considered as shown in Figure 5-6 for the same set of architecture options. The acceptance of the outputs under consideration during a formal review culminates in the establishment of a baseline which is a fixed reference for the configuration of the system under development. Formal change control procedures must then be followed to change a baseline. The

change control is part of configuration management and this was also captured in the SEMP.

"*Any change to an agreed baseline or signed off document shall be executed by means of a change management procedure described in the Configuration Management Plan*."[29]

A separate Configuration Management Plan was utilized to detail the change management procedure. One of the purposes of change management highlighted in the SEMP is to ensure the changes impact is understood so that it does not adversely affect the project.

As part of the risk management of technical management there is evidence of tailoring the development process in order to address risks associated with different sub-systems. Figure 5-10 shows the planning for the antenna sub-system and Figure 5-12 shows the planning for the Correlator Sub-system.

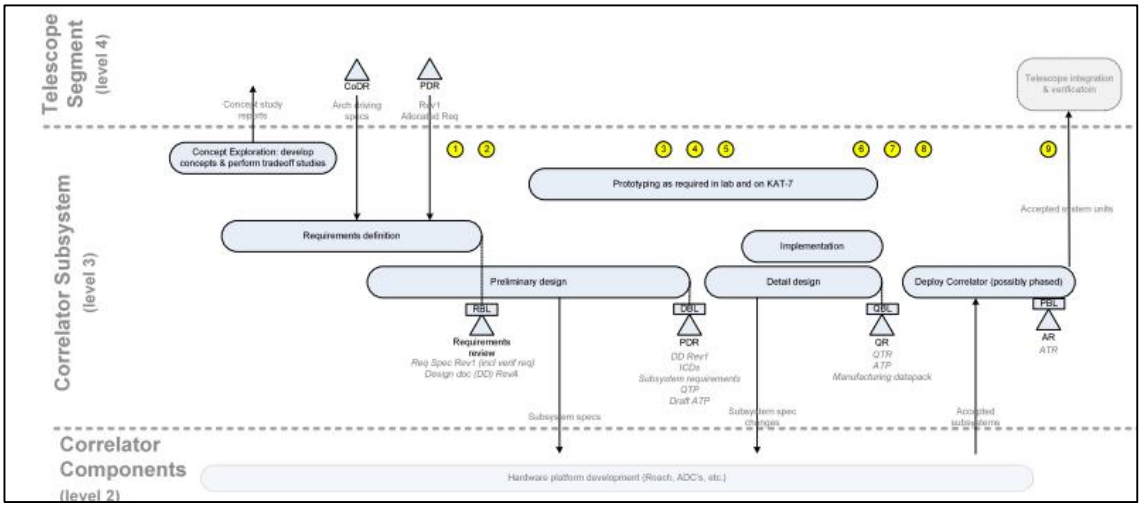


Figure 5-12: Planning of Stages, Baselines and Reviews for the Correlator Sub-system [29]

There are noticeable differences in the overlap of the stages and the points for the reviews and establishment of the baselines. This is further confirmed by the interview evidence below.

"*Yeah, there was a lot of tailoring for sub-systems. What we realized early on because we got such a wide range of technologies is that we needed to customize the process for each sub-system. So we put in an initial proposal in the back of our*

SEMP with tailored diagrams but eventually what we did is we asked each sub-system as part of their requirements review to write a development plan and that development plan basically says exactly how customized the systems engineering approach is for that sub-system. So for each sub-system is customized, what are the key risks for that sub-system and how those key risks are addressed in the development process. And we approved that plan as part of the requirements review." (Appendix B reference 043)

The risks for each technology were different and tailoring was done to address key risks with respect to each technology and was considered as part of the requirements review. The tailoring of the technical management process shows that the process was applied and tailored with consideration of the individual risks.

The structure of the process shown in Figure 5-8 shows the top-down design and bottom-up build approach which is the Vee model as described in the literature review. The use of the Vee model was also confirmed in the paper by Lord [31] as stated below (also in Appendix C Node Report page 54).

"*One of the most fundamental systems development models adopted at the SKA South Africa organisation is encapsulated in the engineering V-Diagram*." [31]

The Vee model is an important consideration as part of the technical strategy and technical planning of the project. The key motivation for using the model was to emphasize requirements driven design and rigorous testing as highlighted by Lord [31]. The use of a development strategy was not explicitly found in the sources of evidence (incremental or evolutionary as stated in the literature review section 2.2.2). However, looking at the structure of the planning in Figure 5-2 by using different development models to build up system capability and organizational capability (technical know-how) this is comparable to an evolutionary strategy where increasing improvement is realised with each solution version based on experience with previous versions. With each version from the experimental development model, Kat-7 System and then to MeerKat there was increasing capability (also increasing complexity) in order to gain experience with the technology and reduce technical risks.

Technology considerations were also part of the SKA development project. A formal measure for technology maturity was however not used but there were considerations made about technology to reduce risk. The following statement from the interview is evidence of the technology considerations made in the project:

"*I think we didn't manage it formally or measure technology maturity formally it was informal. We were extremely aware of it, so in the SKA community, there's different approaches to technology maturity. Some of the Institutions take a very aggressive approach and they take on very high risk technologies. The South African Team specifically, had a very clear strategy to take on technologies that are low risk and can be implemented in the short time scales for Meerkat. So we didn't have formal evaluation metrics for technology maturity but a very conscious technique for example the feed technologies we went for standard you know octave band horn feeds which are mature technology and we knew exactly what we were going to expect.*" (Appendix A reference 031).

From the statement it can be seen that the general approach associated with technology maturity was to utilize mature technology to ensure adherence to the project schedule. This strategy was also captured in the SEMP as shown in the extract below,

"*2.8. Technology strategy*

The MeerKAT project relies on cutting edge technology to be a world class telescope. It is also accepted that the telescope will have a long lifetime and will rely on upgrades to remain a world class facility.

However, the development project is also constrained by a fixed budget and timescale.

Therefore, technologies with the appropriate level of technology readiness shall be chosen at timescales dictated by the project plan, and in line with the system engineering baselines. The required technology readiness level for chosen technologies will increase as the incremental baselines are achieved. For example, during concept exploration it may still be acceptable to consider a number of technology options which are under development. However, at the time of reaching the qualification baseline, the technology must be mature, ready for production, and

must have been proven (through provision of full qualification evidence) to comply to all requirements. Where possible, and in cases where upgrades are foreseen, items shall be designed for modularity and with simple, long-lasting interfaces to ensure easy upgradeability in future. Technologies or components, materials and processes which are known to be at the end of their lifetime or whose expandability is known to be limited, shall be avoided." [29]

The extract above also mentions technology readiness but does not explicitly define what the readiness should be in terms of levels. The last statement in the extract mentions not utilizing technology that is at the end of its life. This statement shows that technology maturity wasn't only considered in terms of the development part of the system life cycle but also for the operational part of the life cycle where technology can impact maintenance in terms of obsolescence. The strategy does not imply all technology must be off-the-shelf and still provides allowance for development but ensures that through the baseline management and qualification it must be proven that the technology is mature enough to be implemented.

A qualification to this claim is that the formality in the technical management may have to be adjusted according to the R&D activity (basic research, applied research or technology development). As stated by Forsberg [8] the formality of the systems engineering process may cause the focus to shift from exploration to adhering to the process. In this case study the focus was on technology development which utilized a large multidisciplinary team and the scale of the development was large therefore a formal process was suitable. The basic research (TRL 1) type of undertaking was not investigated, as the aspects of the SKA project investigated did not involve basic research. As stated by Forsberg [8] the systems thinking concepts should be adopted and the process formality should be tailored accordingly. The summary of the Toulmin model applied to RQ 3 is shown in Figure 5-13.

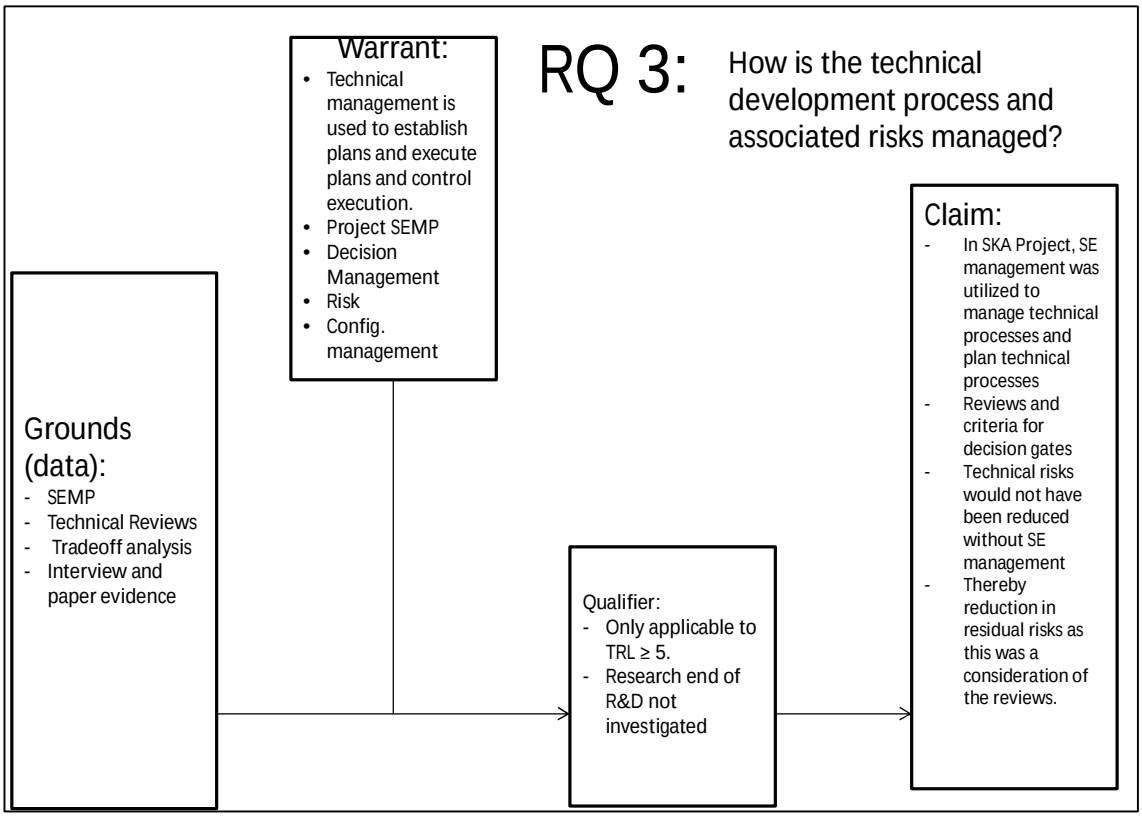


Figure 5-13 Toulmin model applicable to RQ 3

5.5. How are Systems Engineering Methods and Tools Employed in The Project? (RQ 4)

As shown in the literature review in section 2.2.2, there are various systems engineering methods and tools that can be utilized to address technical risks. In the Systems Engineering Handbook the methods and tools are used across the technical processes. To address this research question the methods and tools utilized in the SKA project to mitigate risks will be highlighted. The speciality engineering utilized in the project is also highlighted in this discussion.

From the sources for the case study the following methods were evident:

- Requirements Analysis
- Modelling and Simulation
- Prototyping and development models
- Reliability, Availability and Maintainability considerations

As part of the requirements analysis method a stakeholder analysis was identified from the interview as stated below.

"*The second big set of interactions is with the scientists, so there to get the requirements pinned down. So there we had very good connections to Justin Jonas who is our project scientist and he had contacts with the international community and what we did early in the project is we advertised the Meerkat capability to say these are the technical capabilities the system will have. We asked for proposals for science for scientists to use it. They generated proposals and that created a very clear set of stakeholders so those key science projects are our stakeholders and we elicited all the requirements through them and checked everything with them, the user requirements. From there we used the user requirements to drill down to system and sub-system levels.*" (Appendix A reference 029)

The key requirements for the system were generated utilizing a stakeholder analysis and elicitation technique as part a requirements analysis method. An example of a high-level science requirement as extracted from the Concept trade-off design document is shown in Figure 5-14.

> *"The Karoo Array Telescope MeerKAT will be the most sensitive centimetre wavelength instrument in the Southern Hemisphere; it will provide high-dynamic range and high-fidelity imaging over almost an order of magnitude in resolution (~ 1 arcsec to ~ 1 arcmin at 1420 MHz). The array will be optimized for deep and high fidelity imaging of extended low-brightness emission, the detection of micro-Jansky radio sources, the measurement of polarisation, and the monitoring of radio transient sources."*

Figure 5-14 High level stakeholder Science Requirement [34]

The stakeholder requirements were utilized as parent requirements as part of the requirements definition stage and translated into system functional requirements using functional analysis as stated in the SEMP. The physical architecture is then defined in the preliminary design stage. Utilizing the requirements analysis method ensured that a complete set of requirements was defined which contributes to the quality of the requirements. This in turn allows the high level user requirements to be satisfied which contributing factor to project success.

The evidence of the use of modelling and simulation from the interview is as follows,

"…we used modelling and simulation quite extensively and there's a wide range of different tools that we use. We use mostly in the early phases for verifying requirements and for verifying design. An example of that is the electromagnetic performance of the system, so we did extensive electromagnetic simulations to see what is the best performance that we can get and what is the design that will give is the best performance early and we used that to influence the design and to verify that we can actually meet the requirements." (Appendix A reference 049)

In the extract above modelling and simulation methods appear to reduce technical risk in terms of the design.

Due to the scale of the Meerkat System (approximately 64 dishes in final design) modelling and simulation was also used to analyse the sensitivity of the system for different layouts during the concept definition stage. This was evident in the Concept Options and Trade-off Design Document [34] as shown in Figure 5-15.

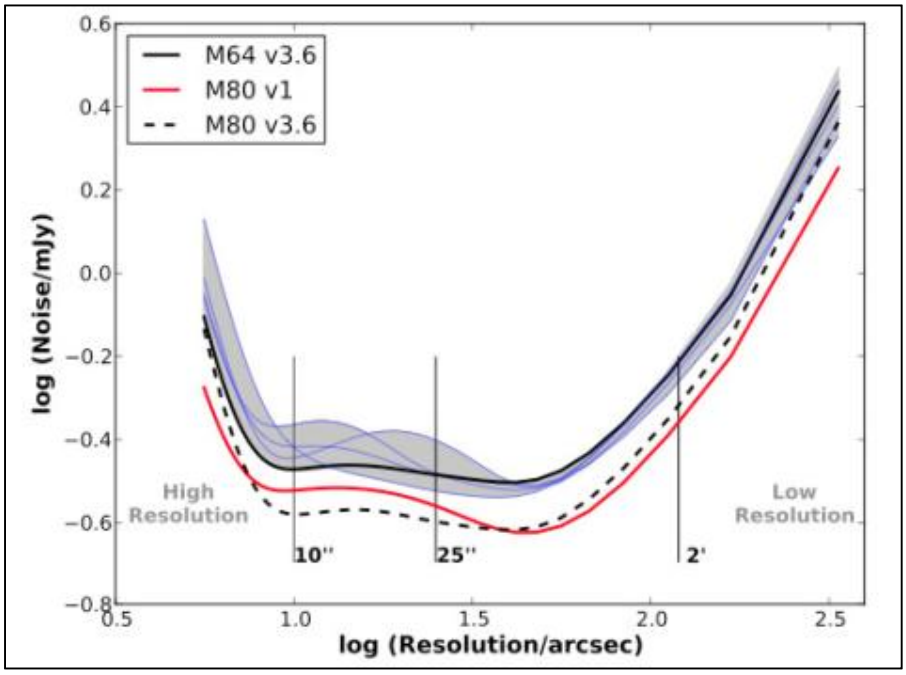


Figure 5-15 Use of Simulation to Analyse System Configurations [34]

The role of simulation in the example above is to reduce the technical risks by providing insight into how the antenna layout will impact performance. This adds value to the project by allowing performance assessment before committing to

construction. Changes once the construction would be started would be much higher if a given layout was found to negatively impact performance.

Another aspect where simulation played a role was in the verification and qualification activities. This evidence to support this is an extract from the paper by Lord [31].

"*Extensive use was made of simulators, which mimicked their hardware counterparts. Subcontractors were instructed to provide the project with such simulators, where necessary, so that the control & monitoring system could be qualified on a representative system in the Cape Town integration lab, before being deployed to site.*" [31]

During integration, an integration lab can be utilized to test hardware items in the bottom-up build leg of the Vee model. Before an entire representative system is built a lower cost integration bench can be utilized to reduce the technical risks by testing during integration.

Prototyping was evident as highlighted in the paper by Lord [31] which showed the use of development models as a risk reduction approach. (Appendix C Node report page 12). This was also evident in the development approach highlighted in the systems engineering presentation [27] as shown in Figure 5-16. Figure 5-16 shows the progression of this from development of technology demonstrators through to various development models (XDM and KAT-7) and building up ultimately to MeerKat and in the future the SKA. Along the development path shown in Figure 5-16 risk is reduced in the development of each successive system as experience is gained with the technology and the development models. Thus, the prototypes allowed the development of the technology and the maturing of the systems engineering capability of the project team to happen in parallel.

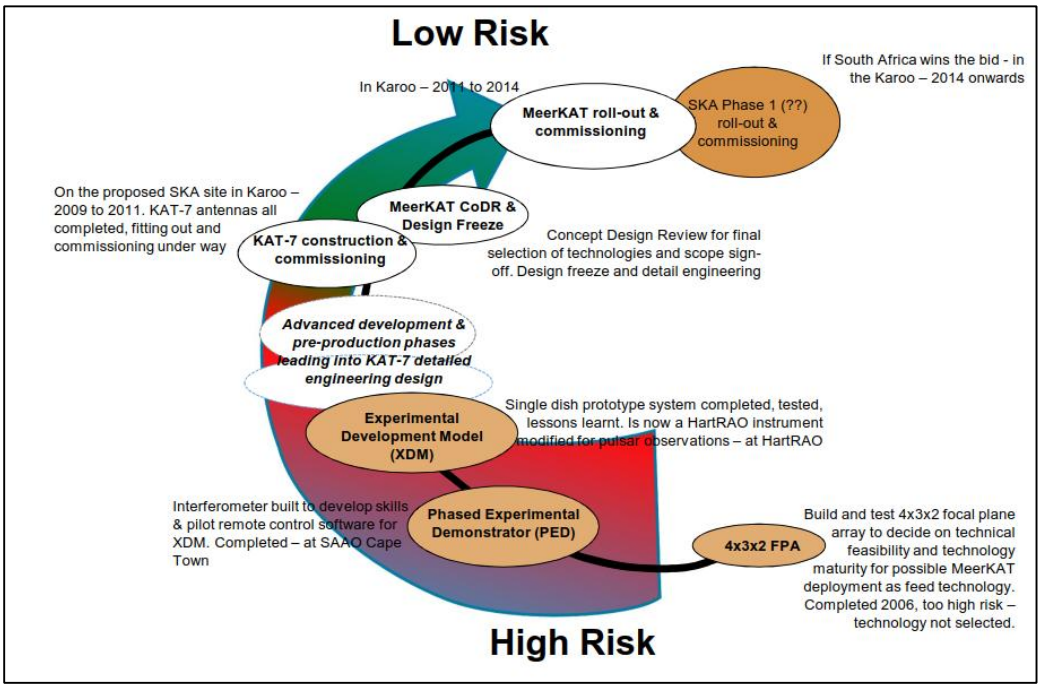


Figure 5-16 Use of Development Models for Risk Reduction [27] (Image: SKA South Africa)

The following tools were found to be evident in the case study sources:

- Requirements management tool – CORE
- Computer Aided Design Tools

As stated in the SEMP the requirements were captured and traceability maintained using a software tool called CORE. CORE also supports the use of a Model Based Systems Engineering Method. The INCOSE Handbook states that in the MBSE method the information on the system is capture in a model or set of models. I

It was also evident from the interview that CORE was utilized to do modelling as well as to print the sub-system specifications.

"*Also examples of that electromagnetic modelling, the mechanical modelling and also system engineering we use CORE. We model the functionality in CORE on the system level*" (Appendix A reference 049)

"*We using core for requirements traceability and requirements management and we capture all the requirements starting off with the user requirements and traced those*

down to system requirements and sub-system requirements and we keep that traceability up and it is still running and we again we matured that capability over time. At this stage the sub-systems a lot of them print out their specs from CORE directly so that's turned out very useful and turned out quite well." (Appendix A reference 051)

As stated in the SEMP a software called Pro-Engineer was used as a computer aided design (CAD) tool. A key aspect highlighted in the SEMP was that this tool was the preferred tool to be utilized by sub-contractors in order to standardize on the information exchange in terms of drawings. The SEMP also provided guidance on the use of the tool for interface control. As this system has multiple interfaces and there are different sub-contractors that may work on different parts of the system, interface control is important.

"*Subcontractor developed items: All mechanical design work by sub-contractors should preferably be in Pro-Engineer.*" [29]

"*CAD interface data: In the event that CAD data is supplied to clients as interface information, the model that is supplied shall be stored in the configuration management system in a zip file, in a non-native Pro-Engineer format (step, iges, parasolid) in order to prevent editing of this interface information. This data shall be issued from the configuration management system. This data shall be referenced in the relevant Interface Control Document, and shall eventually form part of the Interface Control Document.*" [29]

The following speciality engineering methods were found to be evident:

- Value Engineering
- Logistics Engineering (Integrated Logistic Support)

In the SEMP there were guidelines for the use of Value Engineering. (See also Appendix C page 10 for an extract) However in the sources reviewed the application of Value Engineering was not evident.

Logistics Engineering was also evident in the SEMP and the following extract highlights this.

"*The definition of the Logistic Support system shall be based on initial operational and maintenance concepts, in order to integrate any user requirements or constraints into the design of the Logistic Support system. The details of the logistics support management shall be described in the Logistics Engineering Management Plan [3].*" [29]

Lord also mentions that Logistic Support was considered as part of the KAT-7 system. The lessons of supporting KAT-7 in operations would be applied to MeerKat.

"*KAT-7 was always seen as a stepping stone towards MeerKAT. One aim of KAT-7 was to implement an operational system in the Karoo to learn the lessons of how to operate and maintain a radio telescope on a remote site.*"

The importance of the Logistics Engineering and Integrated Logistic Support is that it considers the operational portion of the life cycle of the system. The supportability of the design is considered as well as the desired availability. Further to this logistic engineering focuses on the sustainment and maintenance of the system once it is in operation. As stated in the INCOSE Handbook [3] a major portion of the life cycle cost of the system is from the operation and support of the system and therefore Logistics Engineering is an important consideration.

With the evidence presented above the use of methods and tools was found to be appropriate considering the technical risks of the project.

To summarize the Toulmin model applied to RQ 4 is shown in Figure 5-17.

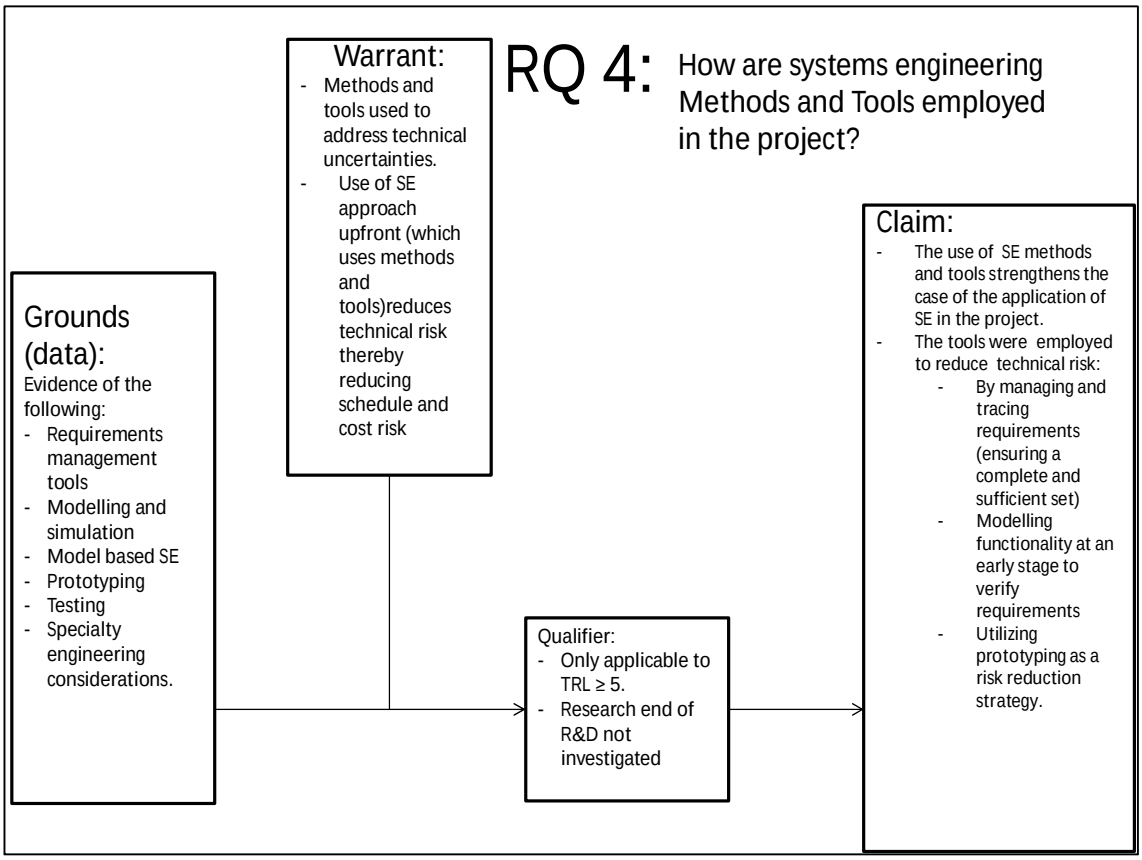


Figure 5-17 Toulmin model applicable to RQ 4

5.6. How is the organization as well as project teams structured and managed to deal with the project? (RQ 5)

RQ 5 was defined to investigate the organisational impact on the project as well as how the project team was managed to deal with the project. The purpose of the question was to understand the organisational context of the project and the stakeholders. Also within the organisation how the project team was managed in dealing with the project and building up knowledge and technical capability. Consideration of the wider environment provides a holistic view of the project environment and would reveal challenges outside of the technical challenges that may also influence the project and that a systems engineer may have to be aware of. This was investigated to determine if any other influences contributed to the project positively or negatively aside from the systems engineering process.

The evidence from the interview highlighted that the organization under which the project was administered and undertaken was the National Research Foundation (NRF) as well as the Department of Science and Technology. The various organizations involved in the SKA project were explained by the Lead System Engineer and as it was understood Figure 5-18 was drawn by the author.

"*The SKA project is administered inside as a sub section of the National Research Foundation so the NRF is part of our larger organization structure but also extending to the Department of Science and Technology*". (Appendix A reference 053)

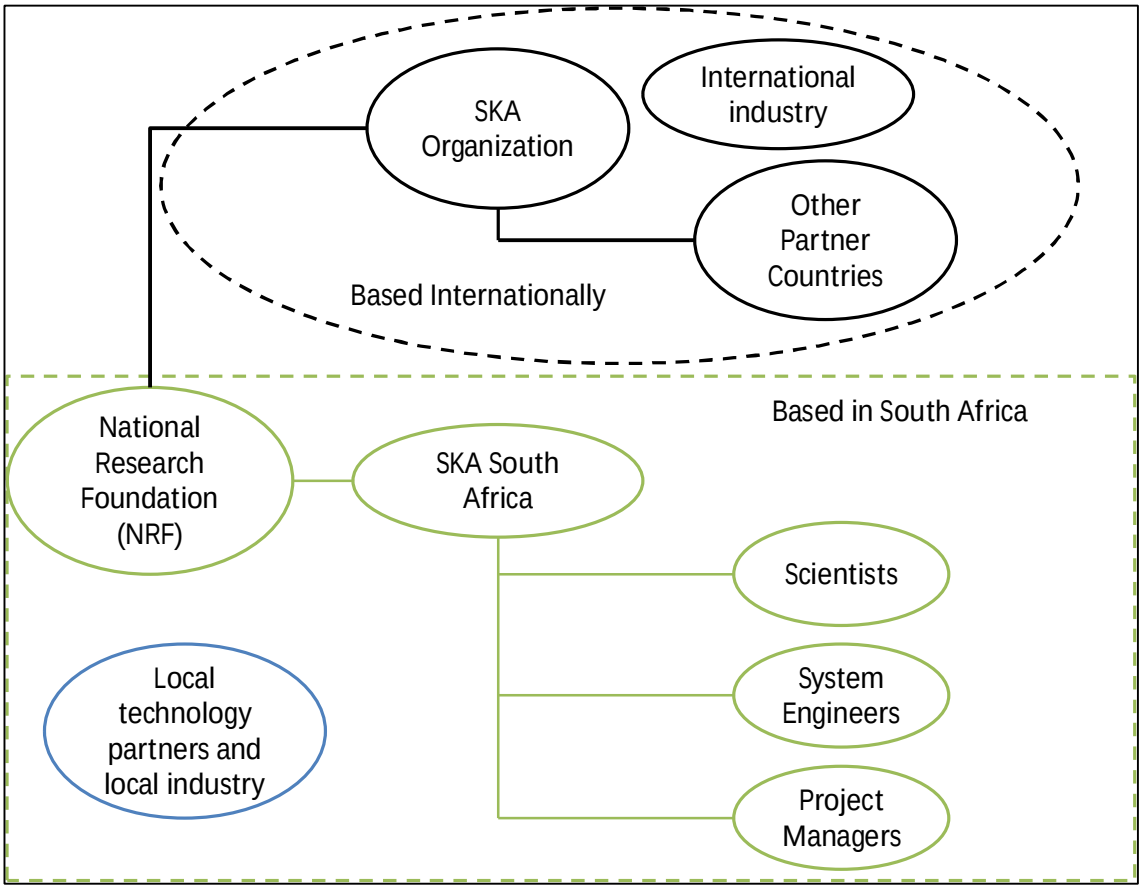


Figure 5-18 Organizational Structure of the SKA Project

The evidence from the interview also highlighted the key stakeholders for the project as well as the interactions and challenges,

"*our stakeholders are funding stakeholders and science stakeholder*" (Appendix A reference 053)

"*we have a lot of direct interaction with them. I think they were very supportive of financial and stakeholder support. I think sometimes we struggle, some of our issues are administrative. Initially the NRF, it is not an organization designed to do large acquisitions, it is designed to manage research and grants so we did have some problems early on to get these processes going where we can do large acquisitions within that organization but that's an example of the challenge we had but it has been improving but besides that we had very good support from the stakeholder, political and financial perspectives*." (Appendix A reference 053)

"*The second big set of interactions is with the scientists, so there to get the requirements pinned down. So there we had very good connections to Justin Jonas who is our project scientist and he had contacts with the international community…*" (Appendix A reference 029)

The influences of the wider project can impact finances and if the right network of stakeholders are not present this can impact requirements elicitation. The systems engineering process may not be able to control these influences but with the systems thinking approach all aspects that can affect the project should be known. Although some challenges are evident such as administrative and process issues a negative impact is not evident.

Some organisational issues highlighted by Lord [31],

"*Developing process maturity. As SKA South Africa was a young organisation, its project management and systems engineering processes still had to be created*." [31]

This highlights that the organisation was started with no previous experience base present and everything had to be created. Figure 5-3 shows that the organizational maturity had to be developed alongside the system. As per the Henderson and Clarke model [14], illustrated in Figure 2-3 of section 2.3, when dealing with something new where there is no previous organisational knowledge the uncertainties are high and the knowledge (component or architectural) has to be built which is evident in this case.

The next consideration of this research questions was the project team. Some of the evidence identified is as follows:

"*So getting the right people and getting them trained and getting our organizational processes and cultures and everything sorted out.*" (Appendix A reference 019)

"*For some sub-systems like the dish structures, the mechanical systems we decided to contract that out to an industry player because it would be difficult to build up that capability in a short period of time. So there we created a very small team in house like just a system engineering and project management capability and contracting out the development work. In some cases for the electromagnetics and the receivers we contracted the whole thing out to EMSS who is a technology partner for us. For the infrastructure we also had a project management and system engineering internally and we contracted out the rest. So it was a mixture depending on how quickly and also it depends on long term for a radio observatory some skills you need in house and some you don't. So we decided we only going to appoint teams of people where we need that capability long term in house, so system engineering, project management, software are basically the areas.*" (Appendix A reference 045)

"*You need the same core team taking it from concept right through to operations otherwise you going to get trouble.*" (Appendix A reference 047)

The project team consisted of a core team that was internal to the SKA organization and those that were partners or sub-contractors. The key driver of this approach was developing capability in a short space of time hence the approach taken. Having an appropriate team with the right knowledge and experience is an important factor in executing the system engineering process correctly. As mentioned by Forsberg [8] a process does not replace engineering judgment. Carrying through the same team from concept through to operations ensures continuity which positively impacts the project.

To summarize the Toulmin model applied to RQ 5 is shown in Figure 5-19.

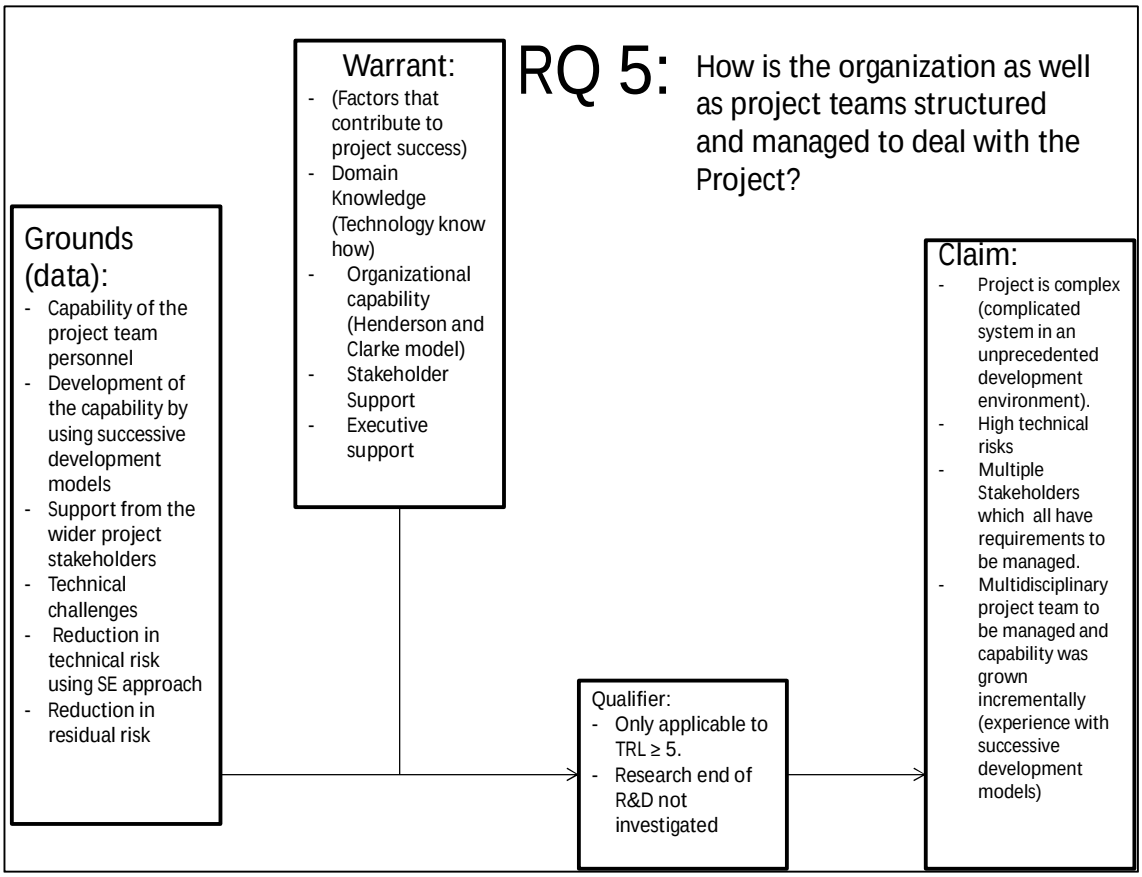


Figure 5-19 Toulmin model applicable to RQ 5

5.7. How does the application of systems engineering reduce uncertainties and associated risks in the Research and Development environment?

In sections 5.2 to 5.6 the sub-research questions were addressed which link back to the central research question of this section. Therefore a summary of the previous discussion will be used to address the central research question.

This research investigated the following:

- The characteristics of a project in an R&D environment and the suitability to apply the systems engineering process
- The technical processes that are utilized in that project and why
- The technical management of the processes to manage technical risks
- The methods and tools utilized to in execution of the processes

- The organization under which the project is undertaken and the structure of the project team that executes the project

As discussed in section 5.2 in the case under consideration the project was complex due to a complicated system requiring a multidisciplinary project team and a harsh operating environment. There were also technical uncertainties due to the unprecedented nature of the project in the South African context as well as the capabilities of the organisation. As a result systems engineering was found to be a suitable approach for a R&D project of this nature.

As discussed in section 5.3, the technical processes that were applied are based on a systems engineering approach. The technical processes allowed the technical risks to be reduced by following a structured approach to identify the relevant stakeholders, elicit a complete set of requirements, define a system to meet the requirements, build and verify the solution against the requirements. The role systems engineering played in this case was that it provided a set of technical processes that reduces uncertainties by increasing the information (stakeholder elicitation) and allowing technical risk to be reduced in a structured way by ensuring the correct system is built.

As discussed in section 5.4 the technical management of systems engineering allowed the sequencing of the technical processes in light of the technical risks associated with the system being developed in the project. The key role of the systems engineering approach is in the definition of a SEMP which stated the process planning, the required outputs from each process for decision making as well as defining the points at which the outputs would be reviewed and the requirement of the review in order to assess technical, cost and schedule risks of the technical processes. The use of baselines and configuration management processes also ensures that changes are managed and controlled in a formal manner.

The methods and tools as discussed in section 5.5 provide the means to execute the technical processes as planned in the SEMP. The methods and tools highlighted are associated with the systems engineering approach and when they are applied across the technical processes play a role in technical risk reduction as discussed in section 5.5.

In section 5.6 the wider organisation was investigated. The key aspect of this is that all the stakeholders should be identified and the various influences understood in order to gain a holistic view of the context of the project. The structure and management of the project team was also investigated. The knowledge and capability of the team has to be considered as it is the team that executes the system engineering process and this has an influence on the project. As stated by Forsberg [8] the process is not a substitute for engineering judgment.

Thus, systems engineering reduces technical uncertainties and technical risks in an R&D environment by application of systems engineering technical processes, technical management and methods and tools. As stated in section 2.2.2 by Honour [9], application of systems engineering to manage technical risks has been shown to positively impact project cost and schedule. Thus applying systems engineering as shown in this research to manage technical risks in an R&D project can implicitly benefit project technical, cost and schedule performance.

A qualifier to this claim is that the application of these must be tailored to the associated level of risk. The formality of the process must also be tailored to the level of complexity and the size of the project team. A team with the required domain knowledge also plays an important role in order to execute the systems engineering processes. Due to the nature of the project utilized as a case study another qualifier identified is that the application of SE will only be for development of technology for TRL 5 or higher.

To summarize, the Toulmin model applicable to the CRQ is shown Figure 5-20.

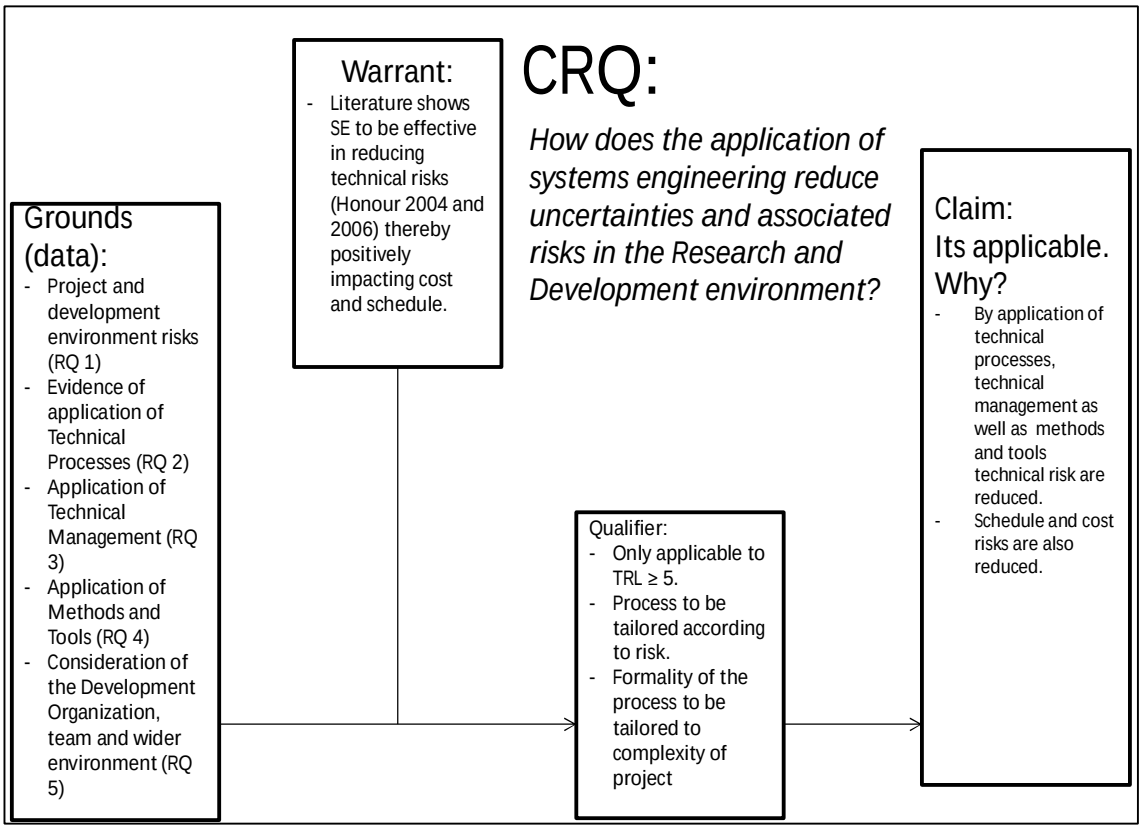


Figure 5-20 Toulmin model applicable to the CRQ

5.8. Summary of Results and Discussion

To summarize, the results and discussion presented in 5.2 to 5.7 will discussed taking into consideration the hypotheses and the relationships to the research questions as established in Table 3-2.

RQ 1 showed that the SKA project is a complex development with high technical risks which is well suited to the application of systems engineering. The systematic risk reduction approach allowed experience to be gained with development models and allowed any fundamental problems to be identified as early as possible. The use of structured stages does not appear to stifle creativity as multiple design options were still considered as shown in Figure 5-11. RQ 1 supports Hypothesis 1 (section 2.3.1) in that a systematic approach promotes identification of problems early in a project. This is however limited to the development portion (TRL ≥ 5) of a research and development project as the basic research spectrum was not investigated.

The evidence to answer RQ 2 could not directly show the value added by applying systems engineering technical processes as stated by Hypothesis 4. In this project there were no metrics to measure the influence of the technical processes on the cost and schedule. Due to the lack of evidence it cannot be directly confirmed that the evidence supports Hypothesis 4.

RQ 2 shows that there are technical processes applied and shows how the process is structured in the SKA project. It is clear that the process was driven by requirements, which supports the first part of Hypothesis 5. The second part of Hypothesis 5 differs from the evidence in that the SKA project had clearly defined stakeholders (customers). Elicitation from the Stakeholders was used to obtain science requirements and the developers did not have to set these requirements. The evidence of a requirements driven process also addresses why the process is structured as shown in Figure 5-8. The structure allows flow down of requirements to ensure a sufficient design by traceability to stakeholder requirements. The bottom up build process allows verification against requirements to ensure adherence to customer requirements. Further to this a common cause of project failure, that was identified in the literature review (page 28), is due to a lack of complete requirements or changing requirements. The requirements analysis and management approach used in this project ensured a sufficient baselined set of requirements and supports the literature that lack of requirements management can contribute to technical risk.

Also shown in the evidence of RQ 2 is how the trade-off analysis early in the development of the system was used in order to evaluate the technical risk and its impact on cost and schedule for a given design. This supports Hypothesis 6 which shows that cost and risk are considered prior to committing to a given design.

RQ 3 shows that the application of the technical processes and the management of the processes to address risks, allows for the realization of a system from customer requirements. As shown in Figure 5-10 the inclusion of reviews at the end of each stage in order to address technical, schedule and cost risks directly support Hypothesis 2. There was evidence of tailoring of the development process to address differing levels of technical risks from each sub-system. This supports the view of the literature that tailoring of the system engineering process is necessary to optimize effort in relation to risks foreseen.

Due to the lack of project data that measures the impact of technical risk on cost and schedule, Hypothesis 3 cannot be fully confirmed. However from previous studies as highlighted in the literature in Section 2.2.2 (page 29 and 30), the application of system engineering has been shown to reduce technical risk which has a positive influence on cost and schedule risk. The evidence in RQ 3 shows that technical risks were reduced and the literature is used to warrant that this has a positive influence on cost and schedule risks which supports Hypothesis 3 to a limited extent.

RQ 3 also presented evidence of technology maturity considerations however there was no evidence of the use of a TRL type metric to measure the maturity of the technology developed on the project. Instead an overall approach to utilize mature technologies in the project was followed as stated in the SEMP in order to reduce technical risks to enable development in short time scales. Even though there was a technology strategy and it influenced development, Hypothesis 7 could not be proven due to a lack of evidence to directly determine its impact on the decision making.

RQ 4 showed evidence of the use of systems engineering methods and tools, for instance modelling and simulations tools and the use of development models, to reduce technical risks. This directly supports Hypothesis 3 which states that methods and tools are used to manage technical risks. In the literature in Section 2.2.2 (page 28), from previous studies it was shown that the application of system engineering reduces technical risk which has a positive influence on cost and schedule risk. The evidence in RQ 4 shows that technical risks were reduced by applying System Engineering methods and tools. Therefore the literature is used to warrant that this has a positive influence on cost and schedule risks which supports Hypothesis 3 to a limited extent.

The evidence presented to answer RQ 5 strongly supports Hypothesis 8. The evidence shows that the SKA SA team did not have any experience in developing radio telescopes and had to build their own knowledge, experience and capabilities in parallel with the development of the system. This is shown by the use of development models and the risk reduction approach as illustrated in Figure 5-3 and Figure 5-16 respectively. The evidence shows that the technical uncertainty was reduced with each successive development model and this also allowed the project

team capabilities to mature as well. In answering RQ 5 evidence was also found that the selection of project team members targeted individuals that had prior experience in key technologies of the project. This allowed the project team to build upon previous component and architectural knowledge and work toward a new design, which supports the Henderson and Clarke model [14].

The CRQ is answered by the evidence presented in RQ 1 to RQ 5 which together shows how system engineering technical processes, technical management and the use of methods and tools all contribute to the reduction of technical risks. The detailed evidence presented addresses the gap identified in the problem statement, that there is a lack of detail in the literature as to how systems engineering is applied to address technical risks in a project.

As supported by the literature from previous studies, a reduction in technical risk by applying systems engineering has been shown to have a positive impact on project cost and schedule.

In terms of the research objectives defined in Section 1.4, the objectives have been met due to the following:

- The SKA Project which is in the R&D environment was utilized as a case study in this research.
- Research questions were defined to focus the research on specific areas. This was refined further by using Table 3-2 and Table 3-3 to focus on the data collection on specific areas of interest.
- A case study research design was used to ensure reliability in data collection and validity of the case study data analysis.
- The case data together with Toulmin's model of argumentation was used to structure and present the results and discussion of the case study in order to answer the research questions.

6. CONCLUSION

The Central research question of this research was defined as follows:

How does the application of systems engineering reduce uncertainties and associated risks in the Research and Development environment?

In order to answer this question a case study approach was applied to investigate the technical process, technical management, the use of methods and tools and the project team was investigated. A case study protocol was utilized to ensure quality (reliability and validity) of the case study research.

The case study evidence of this research supports the view of Forsberg [8] that a structured system engineering approach can be effectively utilized in a project in an R&D environment to manage technical risks. However the result is limited to technology development (TRL ≥ 5) as the project used in the case study did not involve basic research. The use of a structured approach also did not appear to stifle creativity in the project as evidence of multiple options were considered for the design of the SKA.

A further limitation of this research is that a clear relationship between the reduction of technical risk and the associated reduction in cost and schedule risk could not be directly established. This was due to a lack of project performance metrics to measure cost and schedule savings. This limitation does however present a potential opportunity for future research topics to investigate specifically how reduced technical risk results in reduced project cost and schedule performance.

The evidence in the project supports the view in the literature that applying the system engineering approach should be done as early as possible. During the development of the system, modelling and simulation was used to do analysis of design options prior to committing costs to a given design. In a project the scale of the SKA to change a design at a later stage would significantly impact project cost and schedule.

The detailed evidence presented shows that the use of a systems engineering approach in the SKA project addressed many of the top 10 factors that contribute to project failures as identified in Section 2.2.2 (page 28). For instance the project used

requirements analysis to ensure users were involved and their requirements were captured and any changes controlled. The telescope system was not commissioned at the time of doing data collection, thus the system validation data was not available to confirm if the user requirements were indeed met. When the system validation is completed this data can be utilized as a topic for a future research project to investigate if the user requirements were met and to what extent.

There was evidence of a systems engineering risk reduction approach being used in the SKA project. The approach used various development models to build up technical, process and organisational experience in telescope development, operation and maintenance. The SKA SA team successfully designed, built and operated the development models. The use of this system engineering approach supports the view of the literature that systems engineering is effective in managing risks of a complex development project. The considerations of the operation of the telescope in the project also strongly supports the life cycle aspects found in the systems engineering literature. Considering the life cycle allows operational risks to be addressed as early as possible.

Technology maturity was identified in the literature as one of the sources of technical risk. There was no measure of technology maturity used in the SKA project however technology maturity considerations still formed part of the development strategy in order to achieve shorter development time scales. Due to a lack of a technology maturity measure a limitation in this research is that the exact level of maturity for a given technology was not measured and used for decision making. Using a firm measure of technology maturity for decision making was identified as a best practice in the literature. The project team relied on having qualified data and experience to make decisions about technology risk. Therefore the literature is supported to a limited extent in terms of technology maturity considerations.

A key gap to be addressed by the research as defined by the research questions was to show how systems engineering is applied to reduce technical risks. The use of a case study and the evidence presented shows in detail how the systems engineering process was applied. Despite the limitations identified, the case study addresses the gap identified in the problem statement that there was not visibility in the literature of the detailed application of systems engineering processes, methods

and tools to a project. The case study presented can provide insights and guidance in terms of the application of systems engineering to a development project. The case study approach and the framework for data collection and analysis utilized in this research can be further built upon in order to research other aspects of the SKA project or adopted to do other case study research in systems engineering.

7. REFERENCES

[1] https://wayback.archive-it.org/5902/20160210164701/http://www.nsf.gov/statistics/randdef/fedgov.cfm, last viewed 29 March 2017.

[2] Rogers E.M. *Diffusion of Innovations Third Edition*, Collier Macmillan Publishing

[3] Walden D.D, Roedler G.J, Forsberg K.J, Hamelin R.D, Shortell T.M, 2015. *Systems Engineering Handbook Fourth Edition*, International Council on Systems Engineering (INCOSE).

[4] Ferdowsi B. 2003. *Product Development Strategies in Evolutionary Acquisition*, Massachusetts Institutes of Technology.

[5] Boehm B. 2000. Spiral Development: Experience, Principles and Refinements, Carnegie Mellon University.

[6] Schulz et al. 2000. *Development and Integration of Winning Technologies as Key to Competitive Advantage,* Systems Engineering, Vol. 3, No. 4, John Wiley & Sons, Inc.

[7] Thomke S. 2001. *Enlightened Experimentation*, Harvard Business Review, Harvard Business School Publishing.

[8] Forsberg K, 1995, *"If I Could Do That, Then I Could..." System Engineering in a Research and Development Environment - As Illustrated by the Evolution of the Space Shuttle Tiles*, Systems Engineering Journal, John Wiley & Sons, Inc.

[9] Honour E.C, 2006. *A Practical Program of Research to Measure the Return on Investment (SE-ROI)*, INCOSE 2006 – 16th Annual International Symposium Proceedings.

[10] Wingate L.M, 2015, *The Systems Engineering Role in Research and Development*, INCOSE Webinar, www.incose.org.

[11] Hitchins D.K.1992. *Putting Systems to Work*, John Wiley & Sons.

[12] Jaruzelski B, Loehr J, Holman R, 2012. The Global Innovation 1000: Making Ideas Work, Strategy and Business, Issue 69.

[13] Thomke S. February 2001, *Enlightened Experimentation, The New Imperative for Innovation*, Harvard Business Review.

[14] Henderson R M, Clark K B, March 1990, Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of the Established Firms, Administrative Science Quartely, pg 9.

[15] United States Department of Defense, Systems Management College. 2001. *Systems Engineering Fundamentals*, Defence Acquisition University Press.

[16] United States General Accounting Office. 1999. *BEST PRACTICES Better Management of Technology Development Can Improve Weapon System Outcomes.*

[17] Kasser. J, 2010. *Holistic Thinking and How It Can Produce Innovative Solutions to Difficult Problems*, Proceedings of the 7th bi-annual European Systems Engineering Conference (EuSEC).

[18] Whitney D, Crawley E, de Weck O, Eppinger S, Magee C, Moses J, Seering W, Schindal J, Wallace D. ESD Architecture Committee. March 2004. *The Influence of Architecture in Systems Engineering*, Engineering Systems Monograph, MIT ESD.

[19] Honour E.C, 2004. Understanding the Value of Systems Engineering, INCOSE 2004 – 14th Annual International Symposium Proceedings.

[20] Mooz H, Forsberg K. 2004. *Clearing The Confusion about Spiral/Evolutionary Development*, INCOSE 14th Annual International Symposium Proceedings.

[21] Buede M, 2009. *The engineering Design of Systems,* 2nd Edition, John Wiley and Sons.

[22] The Standish Group. 1995. *The Standish Group Report – CHAOS*, Project Smart www.projectsmart.co.uk, last viewed 26 February 2017.

[23] Yin R.K. 2009. *Case Study Research, Design and Methods*, Fourth Edition, SAGE Publications.

[24] Friedman G, Sage A.P. 2001, *Case Studies of Systems Engineering and Management in Systems Acquisition*, Systems Engineering Vol 7, No 1, Wiley Periodicals.

[25] Maxwell. J.A, 2008. *Chapter 7: Designing A Qualitative Study*, The SAGE Handbook of Applied Social Research Methods.

[26] Baskarada. S. 2013. *Qualitative Case Study Guidelines, Defence Science and Technology Organization*, Australian Government Department of Defence.

[27] Wengraf T.2001. *Qualitative Research Interviewing*, Sage Publications Ltd.

[28] Kusel T. May 2012. *Presentation on Systems Engineering Approach, SKA SA*.

[29] Kusel T, Ludick J, Curtolo F. 2010. *MeerKAT Systems Engineering Management Plan*, SKA South Africa.

[30] Karbach.J. 1987. Using Toulmins Model Of Argumentation, Journal of Teaching and Writing https://journals.iupui.edu/index.php/teachingwriting/article/viewFile/821/810Using Toulmin's Model of Argumentation. Last viewed 27 March 2017.

[31] Lord R. 2012. *The Acquisition of KAT-7*, Incose SA Conference.

[32] Marais A.L, Botha D.H. 2012. *Shaping a Development Strategy Based on Lessons Learned*, Incose SA Conference.

[33] Kusel T. May 2012. *Presentation on MeerKat Systems Engineering Overview, SKA SA*.

[34] Kusel T et al. June 2010, *MeerKat Concept Options and Tradeoff*, SKA SA.

8. APPENDICES

APPENDIX A – Square Kilometre Array Case - Interview Transcript

REF:	TRANSCRIPT	NOTES:
001	Ashlin: So yeah, I don't know if you've looked at the questions?	
002	Thomas: I've had a quick look at the questions.	
003	A: Yeah	
004	T: The follow up questions?	
005	A: Hmm, its semi structured so I will pose a question and then you can answer.	
006	T: Yeah, ok.	
007	A: I tried to make them as broad as possible.	
008	T: Ok.	
009	A: Ok so for the first question.	
010	A: In this SKA project what are the most innovative areas, that you think, in terms of you know the technology and things?	
011	T: There's two specific areas I can think of, the one is, the whole project is about performance and costs so to build the most sensitive radio telescope for the limited budget you have. So the two key areas are first of all the sensitivity that's on the receiver, getting the low noise and the receiver going.	
012	T: So the reason there, its you know a 20 Kelvin system temperature system, so if you can save 1 Kelvin noise temperature you can basically get five percent saving on your total project cost, you basically save millions of Rands just by improving your receiver temperature one Kelvin. So the one innovative area is the receiver technology and there's been some innovations to get the receiver noise temperature as low as possible and I think the other big area that we facing is the data rates because there's huge data rates coming out of the system that we have to process so the on the front end it's a few terabits per second of data coming in so it's a high data rate and we've developed in house signal processing boards and those were developed in house in collaboration with University of Berkley in the US and they have been so I think those are the two big innovative areas I can think of that we have been working on.	
013	A: Ok, so in terms of the components and the, they were sort of developed and went through a lot of development?	
014	T: Yeah.	
015	A: Hmm, some of the key challenges facing the project?	
016	T: Well I think,	
017	A: Ok, just to give you an idea of what I have in mind here is in terms of the resources, schedule and obviously there's also technical challenges and the environment, how did that impact the project?	
018	T: I think the biggest challenges for us, one of them, is organizational because we started this project from scratch without any people so we had to grow the organization along with growing the technology and growing the processes. Karoo in the middle of nowhere and its, you know, there's nothing, it was basically sheep farms so we had to	

REF:	TRANSCRIPT	NOTES:
	establish everything from scratch, from infrastructure and up to everything.	
019	T: So getting the right people and getting them trained and getting our organizational processes and cultures and everything sorted out	
020	T: So that's sort of an enabling system for the system engineering work and major challenge. Then the other challenge is that the system is built on the Green Fields sight in the middle of the	
021	A: Yeah.	
022	T: So it's a wide variety of technology that we put in place from infrastructure to mechanical systems, to facilities, electronics and software so it's a wide range of technologies so that was another challenge. Yeah I think those are,	
023	A: If I can just ask as well, the technology environment you working in, did that impact on you as well or is that a challenge?	
024	T: Yeah, as I mentioned, getting the technologies because we want to build a world class system we had to develop world class technologies in a short period of space so luckily we did have the right people coming and we could and I think it's about getting the right people in the industry and there's contractors for example and one of the contractors we use is EMSS in Stellenbosch and they are experts in electromagnetics and low noise receivers. So its getting the right people to build up those key technologies in a very short space of time.	
025	A: In terms of the requirements, because I am sure there are a lot of requirements on the system, was there a lot of interaction? Did you go through a process of identifying your customers or stakeholders?	
026	T: Yeah	
027	A: And did you have to formally capture requirements and keep them?	
028	T: That was a very important part of the process early on in the Project. Obviously our clients are the scientists mainly and our stakeholders are funding stakeholders and science stakeholders. On the funding side we had to find people, I mean we've got Bernie Fanaroff is our project manager and he has got very good connections in the political realm and then we have the scientists so making the benefits visible, you know, to the funders is one big issue so there's interaction with the funders.	
029	T: The second big set of interactions is with the scientists, so there to get the requirements pinned down. So there we had very good connections to Justin Jonas who is our project scientist and he had contacts with the international community and what we did early in the project is we advertised the Meerkat capability to say these are the technical capabilities the system will have. We asked for proposals for science for scientists to use it. They generated proposals and that created a very clear set of stakeholders so those key science projects are our stakeholders and we elicited all the requirements through them and checked everything with them, the user requirements. From there we used the user requirements to drill down to system and sub system levels.	
030	A: Okay, previously you provided me with a SEMP and I think we	

REF:	TRANSCRIPT	NOTES:
	discussed this previously that there was no sort of measure of, at that time you didn't have a measure of technology maturity, ok did you now move to some type of measure to measure technology maturity?	
031	T: No we didn't not on Meerkat project. On Meerkat it was a very, you know I think we didn't manage it formally or measure technology maturity formally it was informal. We were extremely aware of it, so in the SKA community, there's different approaches to technology maturity. Some of the Institutions take a very aggressive approach and they take on very high risk technologies. The South African Team specifically, had a very clear strategy to take on technologies that are low risk and can be implemented in the short time scales for Meerkat. So we didn't have formal evaluation metrics for technology maturity but a very conscious technique for example the feed technologies we went for standard you know octave band horn feeds which are mature technology and we knew exactly what we were going to expect. But for the SKA project they are employing metrics for technology maturity but those are defined and they are going to do an assessment of technology maturity at the preliminary design phase. But its quite difficult to measure quantitatively, its often judgement call.	
032	A: Yeah. The next part of this question is, because you didn't have it in your Meerkat Project , did it impact at your decision gates, did it impact on how you move forward or was there a lot of discussion and did you have to come to an agreement with everyone, how did you do it?	
033	T: I think, as I said it was definitely very important part of the decision making but we didn't do it as I said explicitly we did it very subjectively. We looked at the different technologies and we said and we grouped them as sort of mature technologies and not mature technologies and we said we were going to go for the mature technologies.	
034	A: So you clearly defined which path to take.	
035	T: Yeah.	
036	A: Ok, the next question. In terms of the phases that you have you know the development phases, you do some technology development in that R and D phase and you do an assessment and then you move forward to a full scale or detailed design and development, even though you defined that you wanted to use mature technologies did you find any impact later that you know a technology that you used maybe was not as mature or at a mature state later on?	
037	T: Yeah it did, the example I can think of is the cooling technology. We looked at, because the sensitivity is a key performance driver, we looked at two alternative technologies one is a helium based system which is widely used internationally in radio observatories and then the Sterling system. So we actually went for the Sterling system because it was new, it was a bit of a technology risk we took at that time but we chose it because we saw it as a much lower cost and maintenance, operational and acquisition cost option and we took a conscious risk at that stage and it turned out it wasn't the best technology to use, it was proven in a different application, its used for	

REF:	TRANSCRIPT	NOTES:
	space applications and other telecommunication applications. In those other applications it works fine but for radio astronomy applications it turned out not to be such a good solution. So to an extent it was that the maturity of the technology was proven in a different application but it didn't turn out to be valid for this application. That's one example I can think of.	
038	A: Ok, maybe just to expand on that one. Did you have to develop it and then implement it in your design? How did you approach it?	
039	T: Because it was part of our program Meerkat, we first delivered the first, its actually the cooling solution developed as first of all passive cooling without cryogenics that was the first dish in Hartbeeshoek. Then on the Kat-7 system we tried the Sterling cooler and that didn't turn out to work so well. Then for Meerkat we reverted back to the proven technology so we had the opportunity for the prototypes to implement and build on them.	
040	A: Ok.	
041	T: So Meerkat is actually using the Helium System which works much better.	
042	A: So you tried it on your prototype before. The next question six, again previously I looked at the SEMP and I see that your development model or method there it looks like kind of a top down design bottom up like the Vee type of model from system engineering from your documentation it wasn't sort of clear to me, was there any further tailoring in this for more complex sub systems? If there were deeper levels of complexity did you tailor this further to say we will deploy it in segments or given that you may have had uncertain requirements did it influence your development approach? Was there any tailoring?	
043	T: Yeah, there was a lot of tailoring for sub-systems. What we realized early on because we got such a wide range of technologies is that we needed to customize the process for each sub-system. So we put in an initial proposal in the back of our SEMP with tailored diagrams but eventually what we did is we asked each sub-system as part of their requirements review to write a development plan and that development plan basically says exactly how customized the systems engineering approach is for that sub-system. So for each sub-system is customized, what are the key risks for that sub-system and how those key risks are addressed in the development process. And we approved that plan as part of the requirements review. So that turned out to be a very useful approach, something that we learnt on Meerkat. We didn't do it for KAT-7, but then for KAT-7 we asked for that document as part of the requirements baseline.	
044	A: Just to start over again there, you said there was a development plan and for each sub-system it was tailored according to that development plan. Ok, the project team itself how did you construct the team? I can see from the SEMP itself there are a lot of sub-systems and from the structures to the electronics, how did you structure the team?	
045	T: Well I think a key question there, as I said we have a wide range of	

REF:	TRANSCRIPT	NOTES:
	different technologies from infrastructure to mechanical, to RF electronics, digital electronics and software. So we had to look at each of those disciplines and see what the best way to get that technology up is and running as quickly as possible. For each different technology it worked out slightly differently so for some of them, like for software we decided to do everything in house, we decided we can get good software people and get them up and running quite quickly. For some sub-systems like the dish structures, the mechanical systems we decided to contract that out to an industry player because it would be difficult to build up that capability in a short period of time. So there we created a very small team in house like just a system engineering and project management capability and contracting out the development work. In some cases for the electromagnetics and the receivers we contracted the whole thing out to EMSS who is a technology partner for us. For the infrastructure we also had a project management and system engineering internally and we contracted out the rest. So it was a mixture depending on how quickly and also it depends on long term for a radio observatory some skills you need in house and some you don't. So we decided we only going to appoint teams of people where we need that capability long term in house, so system engineering, project management, software are basically the areas.	
046	A: And just the other question, I didn't state it, but just to follow up as you went from the R&D phase to the more detailed phases did you carry the same people through or was it different people?	
047	T: Yeah that's very important, if we didn't do that you would be in big trouble. You need the same core team taking it from concept right through to operations otherwise you going to get trouble.	
048	A: Ok. Just in terms of the tools that you were using, did you use sort of modelling and simulation during development and for what did you use it?	
049	T: You know I think we used modelling and simulation quite extensively and there's a wide range of different tools that we use. We use mostly in the early phases for verifying requirements and for verifying design. An example of that is the electromagnetic performance of the system, so we did extensive electromagnetic simulations to see what is the best performance that we can get and what is the design that will give is the best performance early and we used that to influence the design and to verify that we can actually meet the requirements. Also examples of that electromagnetic modelling, the mechanical modelling and also system engineering we use CORE. We model the functionality in CORE on the system level, those are just some examples.	
050	A: The next question, did you use a requirements management tool, I think I saw it in the SEMP that you said you use one but did you use it throughout from beginning to end and was traceability maintained?	
051	T: Yes definitely. We using core for requirements traceability and requirements management and we capture all the requirements starting off with the user requirements and traced those down to	

REF:	TRANSCRIPT	NOTES:
	system requirements and sub-system requirements and we keep that traceability up and it is still running and we again we matured that capability over time. At this stage the sub-systems a lot of them print out their specs from CORE directly so that's turned out very useful and turned out quite well.	
052	A: Ok and the last question, maybe its not phrased correctly but, the structure of the SKA organization I mean there's probably wider structures around it, did the wider structures promote the undertaking of the project? Where there certain processes put in place, was there adequate resources provided?	
053	T: I think there are multiple stakeholders, the SKA project is administered inside as a sub section of the National Research Foundation so the NRF is part of our larger organization structure but also extending to the Department of Science and Technology so we have a lot of direct interaction with them. I think they were very supportive of financial and stakeholder support. I think sometimes we struggle, some of our issues are administrative. Initially the NRF, it is not an organization designed to do large acquisitions, it is designed to manage research and grants so we did have some problems early on to get these processes going where we can do large acquisitions within that organization but that's an example of the challenge we had but it has been improving but besides that we had very good support from the stakeholder, political and financial perspectives.	

APPENDIX B – Interview Consent Form

RESEARCH INTERVIEW CONSENT:

This form requests consent from you to participate in an interview for research purposes. The interview is part of a Master of Science in Engineering (Systems Engineering) research that is investigating projects that involve technology development and technical processes in the research and development environment.

As a participant in the research you are expected to answer questions asked by the interviewer. The interview should be approximately 20 to 25 minutes in duration. The following information must be noted in this regard:

- Participation is voluntary, and the participant may refuse to participate without prejudice;
- The participant may withdraw from the interview at any time without prejudice;
- The participant may decline to answer any question;
- The participant may choose to remain anonymous;
- Any information collected shall be treated as strictly confidential and no individuals will be named in the reporting of the research;
- The interviewer will record (audio recording) the interview for accuracy purposes in transcribing. You may decline to be recorded however it must be noted that this may affect the accuracy of the transcripts made of the interview;
- The participant is required to consent to participation below:

I, T. Kusel (name in print) voluntarily consent to participation in the research and have been made aware of the information above and that I am free to withdraw from the interview at any time without prejudice.



Signature

28/8/2019

Date

APPENDIX C – Electronic Files - Case Data Coding Evidence- Nvivo 10 Node Report and Case Study Database