Optimisation of Defence Technology Research and Development Projects using Quality Tools in the South African Defence Industry

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Declaration

I, Vasen Subroyen hereby declare that this research report submitted for the degree (Master of Philosophy: Quality Management) at the Durban University of Technology, is my own original work and has not previously been submitted to any other tertiary institution.

Signature:

______________ 2019/08/23

Vasen Subroyen Date

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Abstract

Defence Technology Research and Development (R & D) projects provide the South African National Defence Force (SANDF) with the cutting edge military technologies that they require. However, reduced defence budgets, wasteful use of resources combined with a costly setup and extended timescales to develop and execute military technologies cost the SANDF millions of rand. This study aimed to investigate suitable quality tools to optimise defence technology R & D project execution with the intention to develop superior military technologies for the SANDF within time and resource constraints.

This study used a case study research methodology that employed the quantitative technique of a survey to obtain data on challenges and the use of quality tools within the South African defence technology R & D project execution environment. Survey questions were formulated on the literature reviewed on quality in R & D projects.

Results from the survey revealed chronic issues with continuous changes to technical requirements and the practice of inefficient quality methods that result in redesign activities of the design concepts. Further analysis of the results showed a direct impact of these practices on project delays and the use of unplanned additional resources. The survey further confirmed the limited use of suitable quality methods tailored for the non-standard and non-repetitive nature of defence technology R & D project execution.

A framework with suitable quality tools for defence technology R & D project execution was developed on Microsoft© Excel and tested during a perception study. The framework was titled Toolbox due to its ability to be flexible where one or a combination of methods can be implemented during defence technology R & D project execution. The purpose of the framework was to reduce the reliance of the project team on inefficient methods that result in project delays and the use of unplanned resources. Finally, conclusions, recommendations and future research in the South African defence industry were discussed.

List of Abbreviations

DOD	Department of Defence
DOE	Design of Experiments
DFMEA	Design for Failure Mode Effects Analysis
DP	Design Parameter
FMEA	Failure Mode Effects Analysis
FTA	Fault Tree Analysis
FR	Functional Requirement
HOQ	House of Quality
OA	Orthogonal Array
QE	Quality Engineering
QFD	Quality Function Deployment
QM	Quality Management
TRIZ	Russian acronym for Theory of Inventive Problem Solving (In Russian, TRIZ means Teoriya Resheniya Izobretatelskikh Zadatch)
R & D	Research and Development
RPN	Risk Priority Number
SANDF	South African National Defence Force
SC	Searching Concept
S/N	Signal to Noise ratio
SN_L	Larger the better system response value
SN_S	Smaller the better system response value
SN_T	Nominal is the best system response value
VOC	Voice of Customer

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Glossary

Corrective Action:	A reactive process that is conducted after a quality inspection to rectify a design in order to improve its quality.
Functional Requirement:	These are SANDF performance requirements that the new equipment must achieve during military operations.
Robust Design:	A design that is evaluated and conforms to controlled factors (design specifications) and uncontrolled factors (environmental factors).
Technical Requirement:	These are requirements where SANDF functional requirements are translated into engineering and scientific parameters according to the design concept. Also referred to as the design parameter.
Trade Off Analysis:	An evaluation process were the technology R & D project team identifies a quality characteristic to be improved on a design, however improvement of this quality characteristic may cause the deterioration of another quality characteristic.
Trial and Error:	An evaluation process that applies back and forth iterations to the design to refine the design until it meets the technical requirements.

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1. INTRODUCTION

Chapter 1 holistically describes the research to be undertaken within this study that delves into challenges experienced within the South African Defence Technology Research and Development (R & D) project execution environment. Furthermore, the research will investigate suitable quality tools to reduce potential inefficiencies in this environment. The chapter then describes the aim, objectives, assumptions, research methodology and rationale for this study. The summary for this research study is finally outlined.

1.1 Background

The National Planning Commission (2010) in its National Development Plan 2030 recognised the critical importance of a strong Defence Technology Research and Development (R & D) base in South Africa. The South African Defence Review (2014) reported that continuous investment into defence technology R & D projects will ensure the development of optimised military technologies. The Defence Review further reasoned that investment in defence technology R & D projects will ensure that the country achieves and maintains its strategic independence by not relying on other countries for military technology and support. Moreover, Jha (2009) emphasised that defence technology R & D also has economic benefits in creating jobs and providing a valuable source for generating new ideas which may have a commercial application. Beyond the economical benefits, Jermalavičius (2009) highlighted the critical importance that defence technology R & D plays in the fight against terrorism, as well the protection of critical infrastructure by means of research and development of new technology. Therefore, the importance of continued investment into defence technology R & D projects in South Africa is necessary to maintain the country's strategic independence and provide protection against imminent threats.

According to the current Guideline to manage defence technology R & D projects, the lower level technology project execution processes consist of scientific and engineering activities (Armscor, 2003). The South African Defence Review (2014) also indicated that current defence technology R & D project activities are focussed on the advanced application of physical science to research and develop military technology. The current Guideline further stated that to ensure the generation of high quality military technologies during defence technology R & D project execution, activities of interpreting SANDF client functional requirements into technical requirements, as well as conducting design and test evaluation are applied (Armscor, 2003). Likewise, the white paper on South African Defence related Industries regarded the interpretation of SANDF requirements, inspections, testing and design evaluation as core quality capabilities that should be retained for defence technology R & D for the SANDF (DOD, 1999). The lower level defence technology R & D project execution activities are unique to any other environment due to the requirement to develop technologies with distinctive capabilities such as weapons and guided missiles. Due to the sensitive nature of the technologies such as weapons that are created through defence technology R & D projects, actual R & D execution activities and its results conducted by the South African defence industry are required to comply with safety and security legislation as shown in Annexure L (DOD, 1999). In terms of the white paper on South African Defence Industries, unique military technologies are to remain classified (DOD, 1999). The disclosure of security classified defence projects could compromise the safety and security of SANDF soldiers during missions. Therefore actual defence technology R & D project execution results or its lower level technical activities may not be disclosed or referenced in this research. For clarification on the lower level defence technology R & D execution processes, Annexure M illustrated the typical defence technology R & D project execution activities.

As discussed in the preceding paragraph, defence technology R & D project execution employ methods of interpreting SANDF requirements into technical requirements, inspections and design and test evaluations to generate quality technology concepts. However, Jha (2009) stated that many countries are questioning the effectiveness of current defence technology R & D activities and its methods in generating quality technologies efficiently. He reasoned that current defence technology R & D projects are shown to be lengthy, risky and an expensive process with some major weapon systems taking between 10 to 20 years to complete while costing billions of dollars. Similarly, the South African Defence Review (2014) agreed that defence technology R & D project methods require a costly setup and extended timescales to research and develop military technology. According to Campbell (2017), the creation of defence products and capabilities for the South African National Defence Force demands a high and continued investment into defence technology R & D projects. However, he confessed that in South Africa this is impaired by the lack of adequate funding and availability of suitable resources. Hence, Magubane (2017) added that severe defence cutbacks are affecting the SANDF's capability to maintain its current mandate including protecting South Africa's borders. Le Roux (2004) admitted that African militaries including South Africa are under great pressure to cut down on their defence budgets and have to struggle to distribute scarce defence technology R & D funds to their best advantage to identify and maintain its technology capability. Likewise, in the US Mandelbaum and Reed (2007) agree that in today's environment of reduced budget and staffing, the Department of Defence can no longer afford the extensive time delays and increased costs that R & D projects have experienced. Le Roux (2004) acknowledged that for African militaries to survive on their current resources, they will have to optimise processes, methods, policies, plans and budgets for improved resource planning and utilisation. This, according to South Africa's primary defence procurement agency, implies that in South Africa defence technology R & D projects must be executed effectively, efficiently and economically for the customer (Armscor, 2015).

The section highlighted the importance of continued investment into defence technology R & D projects in South Africa. It further emphasised that defence technology R & D project execution involves technical activities to research and develop military technology concepts and to the ensure generation of quality technologies, the defence industry employs methods of interpretation of client requirements into technical requirements and inspections, as well as design and test evaluations. However, the current methods to generate quality technologies are being questioned due to evidence showing that project teams continue to execute defence technology projects inefficiently culminating in the increased use of resources and extended deadlines (Defence Review, 2014; Jha, 2009; Mandelbaum and Reed, 2007). Typically defence technology R & D projects are planned, managed and executed over a three year period (Armscor, 2003). However as stated in the literature, projects can exceed this deadline with projects running between 10 to 20 years (Jha, 2009). Of concern and due to the reduction in defence spending in South Africa, problems of technology R & D project delays and excessive use of scarce resources can no longer be accommodated (Mandelbaum and Reed, 2007). Hence experts in the defence industry are requesting that methods be optimised to ensure defence technology R & D technology projects are executed effectively, efficiently and economically for the customer (Armscor, 2015; Le Roux, 2004). This study will investigate the lower level defence technology R & D project execution phase that utilises current quality methods of interpreting SANDF requirements into technical requirements and inspections, as well as conducting design and test evaluations to generate military technologies in areas such as firepower (weapons), protection (armour) and mobility (vehicles) for the SANDF. The research area for this study is highlighted in Figure 1.4

1.2 Statement of the Problem

Considering the commentary in the preceding section with regards to problems of project delays and the use of unplanned resources that have occurred in the South African defence R & D technology industry, concerns have been raised on the current methods used to generate high quality technologies. As stated in the current Guideline, to ensure generation of quality technologies, the defence industry employs activities of interpretation of client requirements into technical requirements, inspections as well as design and test evaluations. According to Kothari (2004), when defining a problem, basic assumptions or perceptions relating to the problem should be identified. Similarly, Kumar (2011) claimed that any assumption or assertion on an issue that the researcher wanted to challenge or investigate can become a research problem. Rowley (2002) further acknowledged that the researcher may speculate from the literature or any evidence. The section will review the quality requirements as recommended in the current Guideline, as well as literature to ascertain the perceived effect that these methods have on the problems of project delays and excessive use of scarce resources. Rowley (2002) added that the collected data should be analysed to support or refute these assumptions. Therefore results and analysis in Chapter 4 will either challenge or validate these assertions using descriptive and inferential statistics.

As discussed in Section 1.1, the literature has raised concerns on the effectiveness of current methods in defence technology R & D project execution to generate quality technologies (Defence review, 2014; Jha, 2009). The Defence Industry acknowledges that defence technology R & D projects are technically high risk and thus requires continuous review and adjustment of technical requirements to ensure deliverables are completed (Armscor, 2003). However, this current approach recommended by the Guideline encourages continual changes to technical requirements. This approach was supported during the research and development of the US stealth fighter aircraft where changing technical requirement challenges resulted in poor quality of the airframe and software that culminated in the aircraft underperforming against its predecessor during testing evaluation. As a result of this quality problem to rework the design, the project timescales and costs increased over time to conduct the corrective action (Defence News, 2014). On other several defence R & D technology projects for the Indian Air Force, a report compiled by the Auditor General revealed frequent changes to technical requirements created unclear design objectives leading to redesigns which adversely impacted the time and cost and finally termination of several projects without attaining the objective. It was later identified that these changes to the technical requirements deviated from the client's initial requirements and consequently did not meet the client's expectations (Comptroller and Auditor General, 2015). Jha (2009) admitted that project delays and cost overruns in defence R & D technology projects are likely to occur owing to the changed technical requirements late during the technology R & D phase resulting in performance issues. He exclaimed that this problem is a global phenomenon. As shown above, the Defence Industry is currently plagued by recurring changes to requirements of design activities which are introduced late in the defence technology R & D project execution stage. The challenge for the Defence Industry is that these changes lead to redesign activities requiring extensions in the project completion time and the use of unplanned resources to complete the design concept. According to Thompson (2015), late phase technical requirement changes may result in time consuming modifications, software requirements changes, hardware requirements changes, implementation changes, verification test changes, integration changes, remanufacturing and reinstallation work. He further acknowledged that the effect of these late changes to requirements might also result in failure to complete the project on time and within budget. Therefore, it can be assumed that the Defence Industry should take cognisance that the paradigm of continuous review and adjustment of technical requirements late during the technology R & D project phase can lead to further design modifications to the concept, culminating in delays and also in the use of unplanned resources.

Another method used to generate quality technologies as recommended in the current Guideline is the use of post deliverable quality inspections. The Defence Industry applies quality methods to technology R & D projects upon completion to assess the compliance of contractual deliverables (Armscor, 2003). The Guideline suggests that quality inspections are conducted at the end of an activity when the deliverable has been finalised. These deliverables may include design reports, simulation reports, test reports, literature study reports or hardware of design concepts. In some instances, quality inspections conducted upon completion of a deliverable have resulted in project delays and the use of unplanned resources. El Haik and Shaout (2010) confirmed that conventional quality methods can be characterised as ex post facto (after the fact) practices that utilise information from already completed technology R & D activities such as tests to validate the quality of the product. They suggested that organisations that use this method frequently suffer from huge development costs, lengthier period to market, sub-standard quality levels and a minimal competitive edge.

Furthermore, the Guideline for defence technology R & D project execution recommends that the necessary corrective actions be taken to fix non-compliant deliverables (Armscor, 2003). This implies that once a quality inspection has been conducted and has revealed quality problems on the deliverable, it may lead to corrective action such as a redesign of the technology concept to resolve the problem. The effect of these activities of redesign culminates in delays and the utilisation of additional funds, scarce resources such as labour and material. Gryna (2001) defined redesign as costs of failure to meet customer requirements and needs. Therefore, it is perceived that by implementing quality methods only after completion of a deliverable may lead to corrective action and subsequent modification (redesign) to optimise a design concept which could delay the completion of the R & D technology project and make use of unplanned resources.

Hence from the evaluation of the literature, it is apparent that problems may arise when technical requirements are adjusted late in defence technology R & D project execution or when quality methods are practised upon completion of a deliverable especially when it requires corrective action. Therefore, this study will explore alternate quality tools that proactively optimise defence technology R & D project execution effectively and efficiently by reducing project delays and the use of unplanned resources.

The current Guideline recommends that design and testing evaluations are important methods in defence technology R & D projects to generate high quality technology. Jha (2009) confirmed that defence technology R & D projects involve core activities of testing and experiments to develop and optimise military technologies. Moreover, Wingate (2013) agreed that testing is used to determine the quality of compliance to requirements in technology R & D projects. One of the most common test methods that is used to assess quality of design concepts in defence technology R & D projects is the design test cycle process. Powell Morse (2016) revealed that the iterative design test cycle process is a relevant method that was initially used on defence technology R & D projects such as the prototype hypersonic aircraft. However, according to Walker (2018), the defence industry is attempting to replace the lengthy design test cycle process with other efficient methods. Moreover, Powell Morse (2016) confessed that this method may create costly redesigns that can negatively impact on the time frame and costs of the project. Taguchi (2012) illustrates the design testing cycle process used to determine the quality of compliance to requirements in Figure 1.1. Taguchi (2012), using this figure, explained that a design concept quality is validated through tests and if the design concept fails to meet the requirements, it is redesigned. Yang and El Haik (2003) admitted that this approach leads towards continuous cycles of redesigning to resolve the quality issues in the design, thus culminating in a common activity referred to as firefighting. Tech Target (2009) defined firefighting as an urgent and unplanned distribution of resources that is required to resolve an unexpected challenge immediately. Of concern, Tech Target (2009) acknowledged that the need for firefighting may indicate poor planning and is likely to consume resources that were originally committed on another activity. Taguchi (2012) highlighted that this cycle of firefighting consumes more than 70% of resources. Therefore, in view of the design test cycle process mentioned above, it can be inferred that the current design test cycle process adopted by the Defence Industry makes use of endless cycles of firefighting or corrective action that utilises significant resources. Shiu et al. (2013) admitted that this method only solves problems when the problem becomes apparent from inspections and tests administered. Similarly, defence technology R & D project management recommends the use of quality control methods upon completion of a deliverable (research reports, design reports, test reports) and thereafter sanctions the use of corrective action (redesign) to fix the design.

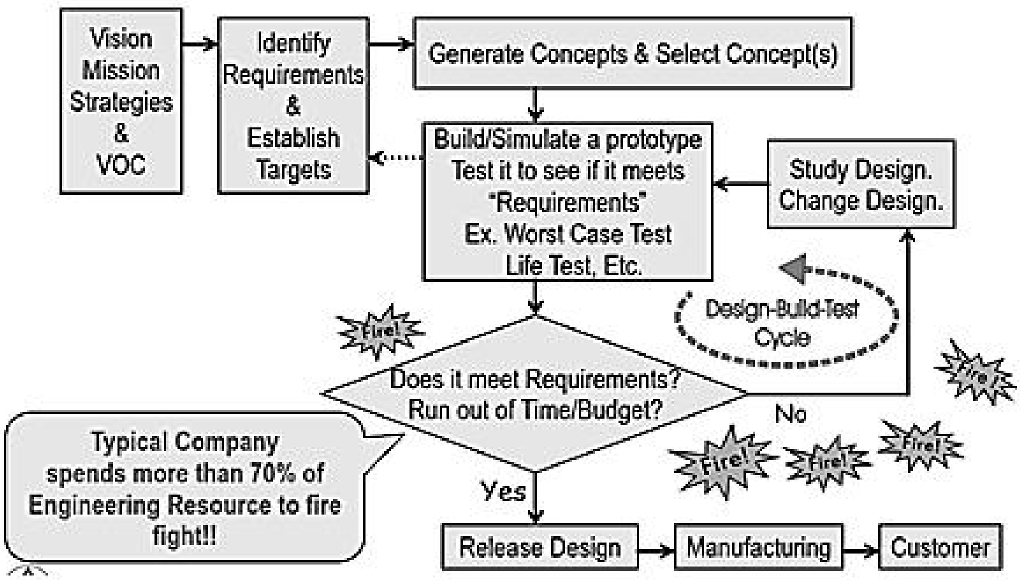


Figure 1.1 Design Test Cycle (Source: Taguchi, 2012)

As previously mentioned, the iterative design test cycle is a popular tool in defence technology R & D projects. Shiu, Jiang and Tu (2013) listed that popular tools applied during the testing process are large sample size testing, Trade Off analysis, Trial and Error and the use of superior materials and components to optimise the design. Shiu et al. (2013) stated that to ensure successful inspections and testing, the R & D project team requires increased test sample sizes to improve problem detection rate on designs. Though the use of large sample tests may improve the quality of the design concept, it does, however, require a large amount of time and resource. Within defence technology R & D projects it may be a challenge to test a high number of samples to various test conditions due to current defence budget constraints. Hence, it makes business sense to investigate alternative quality tools that utilise fewer resources.

As mentioned in the preceding paragraph, the method of Trade Off analysis is another quality method used by the defence technology R & D project teams to improve design concepts during the design testing cycle process. According to Kamel (2017), conducting Trade Off analysis on conflicting characteristics of mobility, firepower and armour protection on armoured vehicles is a common method used in defence technology R & D projects to improve technology. Shiu et al. (2013) indicated that when using Trade Off analysis, the R & D project team identifies quality characteristics to be improved on a design and conducts modifications to the design to improve that characteristic. However, they highlighted that the disadvantage of this method is that the improvement of one quality characteristic may cause the deterioration of another quality characteristic. Yap (2012) cautioned that in defence technology R & D projects such as armoured vehicle design, too thick armour can create added ballistic protection for the occupant but would on the downside add weight to the vehicle, consequently increasing fuel consumption and reducing the mobility of the vehicle. Contrary to this approach, the intention of defence technology R & D projects is to research and develop superior, military solutions for the SANDF and this means improving all characteristics of the design concept instead of finding a Trade Off between characteristics which could result in an inferior design.

As highlighted by Shiu et al. (2013) Trial and Error experimental test method is another common method used by technology R & D project teams to optimise designs during the design testing cycle process. Trial and error testing is still widely practised in the defence industry. MacAskill (2017) reported that according to the UK Ministry of Defence (MOD), failures as a result of Trial and Error testing are part of the inevitable process of defence technology development. Shiu et al. (2013) stated that when R & D teams explore new designs, they use the experimental method of experienced based Trial and Error to refine the design until it the meets the requirements. Russian military designer Genrich Altshuller who studied thousands of designs identified a common problem with the Trial and Error method (Altshuller, 2007). This is illustrated in Figure 1.2 where Altshuller (2007) explained that in the Trial and Error method, in order to get to the solution, the researcher develops a searching concept (SC) and begins to attend to the problem in a certain direction. He further added that later it becomes obvious to the researcher that that whole SC is wrong and then the researcher then returns to the original problem and introduces a new SC that moves in another direction. Thus this back and forth iterations to the design occur resulting in many SC’s being created throughout the Trial and Error method. According to Shiu et al. (2013), the disadvantage is that once the design has met the requirements, the technology R & D project teams tend to choose superior class components and materials to control variability within an acceptable range. Mehta (2014) pointed out that for defence technology R & D projects, there is neither room for excessive timescales nor Trial and Error testing as the delivery of successful results to the customer is becoming increasingly high. Hence activities of defence technology R & D project execution should aim to be efficient and effective in delivering successful solutions to the SANDF within the planned timescales and costs.

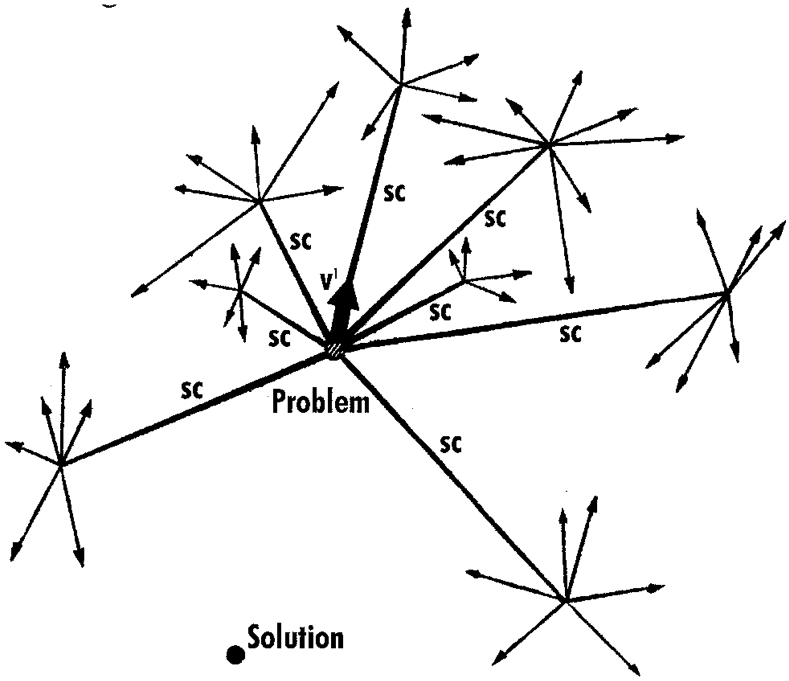


Figure 1.2 Trial and Error Search Method (Source: Altshuller, 2007)

From the preceding sections on the test cycle process that uses large sample size testing, Trade Off analysis, Trial and Error and the use of expensive material and components to optimise design concepts, it is evident that these methods are time consuming and costly on R & D projects. The common activity that resonates with these methods is the need for corrective action or firefighting through redesigning to optimise designs.

From literature and the Guideline, it is apparent that the Defence Industry currently implements methods of continuous review of technical requirements, post deliverable quality inspections and design and test cycle process to generate quality technologies. Literature has highlighted that these current methods result in firefighting (corrective action) activities of redesign culminating in the use of unplanned resources and project delays. A path diagram has been created in Figure 1.3 to illustrate the apparent causal relationship between current quality methods and challenges of the use of unplanned resources and project delays. According to Kothari (2004), a path diagram can be drawn that reveals visual relationships between independent and dependent variables. Cooper and Schindler (2014) defined independent variables as presumed causes and dependent variables as presumed effects. They further mentioned that the term variable is used as a synonym for the term construct and exclaimed that constructs are presumed to exist but must be further tested. Chapter 4 will aim to validate the causality shown in Figure 1.3 through survey results and hypothesis testing.

Madhu and Balakrishna-Bhat (2011) emphasised that it is essential to develop defence technologies which can survive all future imminent threats and this means identifying new methods in design and testing for optimisation of design concepts. Thus, this study will investigate alternate quality tools to optimise the execution of defence technology R & D projects to reduce the problems of increased resource use and project delays and generate high quality technologies.

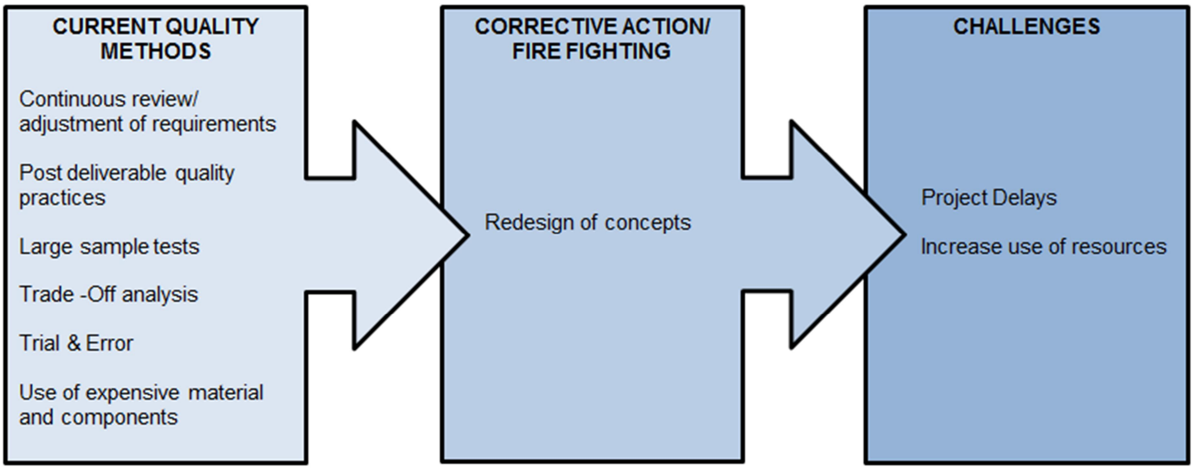


Figure 1.3 Causal relationships between variables (Source: Researcher's own construction)

1.3 Aim of the Research

The aim of this research is to identify suitable quality tools to optimise defence technology R & D project execution by reducing resource use and project delays and generate high quality technologies in the areas of firepower, protection, mobility, sustainability and reconnaissance for the SANDF.

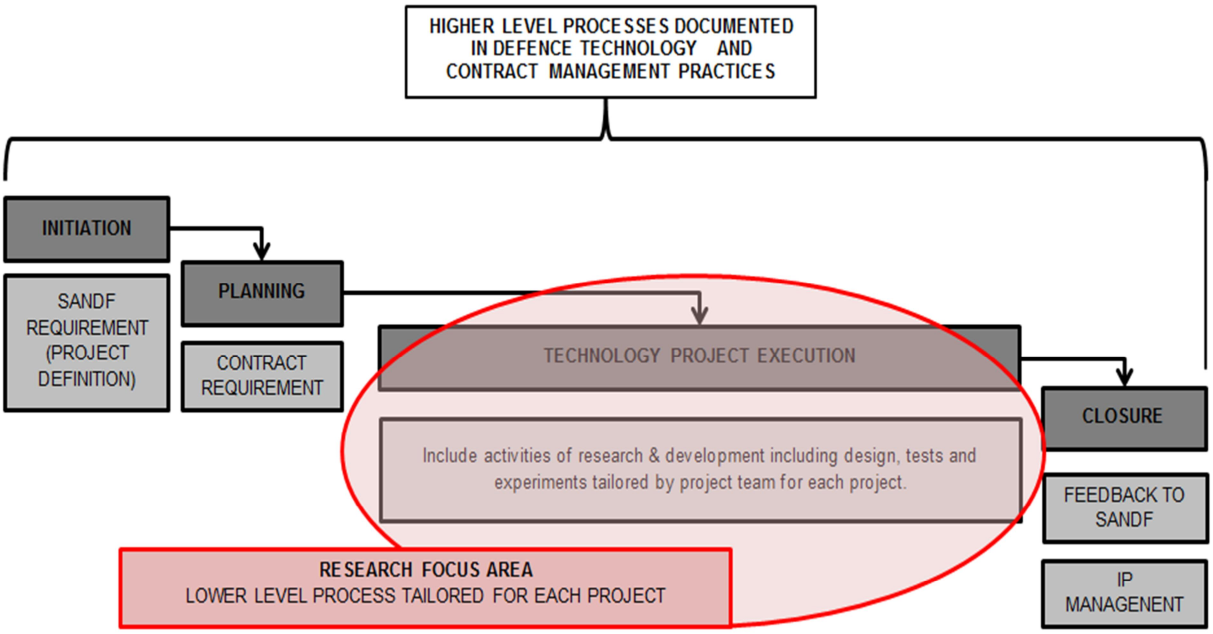


Figure 1.4 Defence Technology R & D Project Execution Environment (Source: Researcher's own construction)

1.3.1 Study objectives

- To identify, using a survey, challenges experienced by project teams that are generating redesign activities culminating in project delays and use of unplanned resources during the execution of defence technology R & D projects.
- To identify from a survey, suitable quality tools that are applied during the research (definition) and development (design and testing evaluation) phase to optimise the execution of defence technology R & D projects.
- To develop a framework with tailored quality tools based on literature and survey results that the project team can adopt during the execution of defence technology R & D projects.
- To conduct a perception study of the developed framework with quality tools to determine suitability for defence technology R & D project execution application.

1.4 Rationale of the Study

The focus of this study is to minimise potential inefficient methods by implementing appropriate quality tools within the technology R & D project execution environment of the South African Defence Industry. Furthermore, Madhu and Balakrishna-Bhat (2011) highlighted that the well-being of a soldier's life is taken seriously and it is critical to develop frameworks with novel technology R & D methods for optimisation of military technologies such as armour materials which can survive all new threats, including those from terrorism. Therefore, this research will identify a novel framework to effectively implement quality tools for defence technology R & D projects execution with the intention to develop optimised military technologies for the SANDF within time, budget and performance constraints

1.5 Methodology

The research method that will be suited for this study is a single case study method which adopts an empirical approach that examines an event within its real life setting. Thus this study will focus on the on real life challenges within defence technology R & D project execution environment in an effort to gain more insight into these issues. Rowley (2002) cited Eisenhardt (1989) who mooted that case studies are tailored for new research topics or areas for which existing theory seemed to be insufficient. Likewise, the research area for this study is on defence technology R & D project execution environment which is an area where limited research to date has been conducted. The study will be based on a case study research approach that makes use of a quantitative method of a survey questionnaire to obtain data.

A convenience non-probability sampling method will be used for the pilot study, as well as the perception study to evaluate the quality toolbox framework that will be developed. A non-probability purposeful sampling will be employed for the main study. A sample of 5 respondents will be used for the pilot study. The sample size for the main study will be 250 respondents of the total population of approximately 500 employees within the South African defence technology R & D project environment. Finally, the sample size for the perception study will be at least 10 respondents. The data collection method is via an email questionnaire that consists predominantly of closed-ended questions that are measured on a five-point Likert scale. Analysis of data collected will be done through descriptive statistics and inferential statistics (hypothesis testing) to validate the challenges and the use of quality methods in defence technology R & D project execution. The research methodology adopted for this study is shown in Chapter 3.

1.6 Scope

This study will be limited to the lower level project execution stage of Department of Defence (DOD) funded technology R & D projects in South Africa that satisfy the research and development needs of the SANDF up to Technology Readiness Level 5. The study is limited to SANDF research and development staff officers, researchers and development project managers, research scientists, engineers and research support staff who are part of the defence technology R & D project team. The sample size will be 250 respondents of the total population of approximately 500 employees within the South African defence technology R & D project environment.

1.7 Assumptions/Limitations of study

According to Leedy and Ormrod (2010), in research nothing is left to chance in order to prevent misunderstandings, and assumptions are determined by asking what is taken for granted with regards to the problem.

The following assumptions (limitations) refer to this research study:

- Research and development technology and product development literature are pertinent to defence technology R & D project execution environment up to technology readiness level 5.
- The inefficient methods identified are only quality related issues within the defence technology R & D project execution environment up to technology readiness level 5.
- Selected respondents from defence technology R & D project execution environment would be willing to participate in the study and provide honest and objective responses.
- Selected respondents have suitable knowledge and experience in the defence technology R & D project environment.
- The sample selected will be representative of the South African defence technology R & D project execution environment.

1.8 Ethical considerations

Welman, Kruger and Mitchell (2010) defined essential ethical considerations to which the researcher should heed that being:

- The researcher should acquire the necessary permission from the respondents.
- The respondents should be guaranteed of their right to privacy.

- The respondents should be guaranteed that they will be indemnified against any physical or emotional harm.
- The researcher should not influence or treat respondents as numbers or objects.
- The respondents will clearly be made aware of the nature of the study being conducted.

Based on the recommendations aforementioned for this study, the researcher has submitted a letter of information and letter of consent confirming the following to the survey respondents:

- The background of the study which is defence technology R & D projects are experiencing delays and unplanned use of resources and there is a need to execute R & D projects efficiently, effectively and economically.
- The benefits of the study which is to develop a framework incorporating quality tools to optimise defence technology R & D project execution and reduce inefficiencies.
- Assurance of the respondents' right for his or her personal information to be kept private.
- Assurance that the respondent will not be subjected to any physical or emotional harm during the survey.
- Permission from the respondent to participate in the survey.

Furthermore a Gatekeeper Letter was obtained from the Organisation that granted permission for the survey to take place.

1.9 Outline of Research

The following outlines the chapters of this research study.

1.9.1 Chapter 1 - Introduction

A holistic perspective of the proposed research to be conducted within the South African defence technology R & D project execution environment.

1.9.2 Chapter 2 - Literature Review

Literature review on quality tools that are relevant to technology research and development projects is presented in this chapter.

1.9.3 Chapter 3 - Research Design

This chapter describes the research design and research methodology process from formulating and issuing a pilot study, main study and perception study measuring instruments (questionnaire) to how data is to be collected and analysed.

1.9.4 Chapter 4 - Results

Collected data is analysed where findings are linked to theory in the conceptual framework.

1.9.5 Chapter 5 - Conclusion & Recommendations

Based on findings of the survey and examination of literature, a framework with tailored quality tools will be developed to optimise defence technology R & D project execution, and thereafter a perception study will be conducted to ascertain the framework's effectiveness.

1.10 Summary of the chapter

This chapter outlined the activities of the Defence Industry. African militaries such as the South African National Defence Force (SANDF) are forced to reduce their defence spending and yet they are obligated to increase their peacekeeping duties on the continent. It showed that in order for the military to survive, they have to optimise technology R & D methods for improved resource planning and utilisation. These activities include the important defence technology R & D project execution phase to research and develop new generation military technologies.

Unfortunately the current quality methods to optimise defence technology R & D project execution activities were assumed to be inefficient, time consuming and costly leading to corrective action and firefighting activities of redesign. Therefore, the aim of the study is to identify alternate quality tools to optimise defence technology R & D project execution by reducing the use of additional resource and project delays and generate high quality technologies for the SANDF.

The next chapter will review literature from various authors' on alternate quality methods which are regarded as more efficient.

2. LITERATURE REVIEW

2.1 Introduction

This chapter discusses the concept of Quality tools in technology R & D projects. From literature, recommendations for selecting suitable quality tools for defence technology R & D projects were identified. Based on these recommendations various quality methods were reviewed. The chapter identifies the synergy between the various quality tools that will provide a basis for the development of a quality toolbox framework to optimise the defence technology R & D project execution phase that utilises current methods of interpreting SANDF requirements into technical requirements, inspections as well as conducting design and test evaluations to generate quality military technologies for the SANDF.

An initial review of the literature was conducted to seek current methods related to quality management and quality engineering both from local and international defence and military organisations. However, the literature revealed limited or no focus in the area of quality in defence technology R & D projects. It is highly unlikely that there are no quality practices implemented in these R & D industries but rather that the information is confidential, hence the absence of these practices in the public domain. As stipulated in the white paper on South African Defence Related Industries, defence technologies should remain classified because developed technologies such as weapons and sensors need to have a competitive edge on the battlefield (DOD, 1999). Hence strict compliance to Legislation as shown in Annexure L must be adhered to for all defence related projects. Fortunately, from the South African Defence Review (2014) standpoint, the majority of pertinent defence technologies are established in the commercial technology R & D environment, resulting in defence forces becomingly heavily dependent on the application of commercial and civil technologies. Furthermore, the Defence Review highlighted that the SANDF will need to exploit future technology opportunities through the use of civil technologies. Hence the literature reviewed in this chapter predominately originated from the commercial and civil technology R & D project environment.

It should be highlighted, that this chapter cited both old and recent references. Bohannon (2014) reported on a study conducted by Google Scholar researchers which revealed a clear trend where the use of old references, at least 10 years older than the study citing them, has increased steadily. Furthermore, he also cited an earlier study by Lariviere (2007) which explained that reference to older literature was beginning to rise since the 1960s and 1970s. He suggested that many researchers are looking further back in time to find papers worth citing so as to improve the quality of the research. Thompson (2013) also confirmed that there are a few research areas where there has been no research activity for a long time and thus researchers need to look deeper into the past in order to find topics which are well established. As explained earlier in this section, new research in this area of quality within defence technology R & D projects has been limited. Thus, established theory relevant to this area was at times identified in older literature. Hallas (2016) supported the notion that older references that contain influential theories do have their place in thesis writing as do the most up-to-date references. She concluded that regardless of the age of the reference, researchers should indicate what references and writers are relevant to the study. Likewise, relevant authors cited in this review are pioneers in such methods as Axiomatic Design, TRIZ and Taguchi and hence they were selected even though they may be perceived as being outdated.

2.2 Insight into selecting suitable Quality tools

This section provides insight in selecting suitable quality tools for activities of defence technology R & D project execution.

Boyle (1999) highlighted that certain quality methods may not be suited for R & D projects, for example, control charts, which are used to represent data from a highly repetitious environment. Thomke and Reinertsen (2012) emphasised that in the world of manufacturing, tasks are repetitive and activities are reasonably predictable, whereas in R & D product development many tasks are unique. They further highlighted that the failure to appreciate critical differences between manufacturing and development gave rise to several problems that undermine the planning, execution and evaluation of R & D product development projects. Similarly, in the technically high risk defence technology R & D project environment, solutions are unique and non-standard by nature and quality methods that are effective in this non-repetitive environment should be investigated.

Smailagic and Smailagic (2014) drew attention to the fact that it is not possible to standardise all the details in R & D projects as the efficiency and creativity of the researchers would suffer. Likewise, within the defence technology R & D projects, standards and specifications are aspects not normally addressed in the technically high risk technology environment. Zala (2015) cautions on the use of total quality control systems such as Six Sigma which is applied to all aspects of the production process. He claimed that a total quality control system such as Six Sigma may create rigidity and bureaucracy which will result in delays and stifle creativity. Moreover, the current Guideline states that defence technology R & D projects are technically high risk in nature and hence this generally requires a flexible method in its execution process (Armscor, 2003). Therefore, this research will not eliminate flexibility from defence technology R & D project execution but rather aim to find a balance between flexibility and quality tools. Hence, a more flexible method of implementing quality tools needs to be identified.

Boyle (1999) advised that an effective quality program in R & D projects can be implemented by using different combinations of quality methods. Smailagic and Smailagic (2014) confirmed that a quality toolbox which is modular and enables the manager to select the relevant quality method when needed could be developed for R & D projects. Thus, rather than implementing a rigid system throughout the defence technology R & D project execution environment, it will make sense to extract applicable methods from proven systems such as Six Sigma to create a toolbox. A flexible method is necessary as it will allow the R & D researcher the autonomy to think of innovative military technologies for the SANDF. Similarly, this research study will not eliminate flexibility from defence technology R & D project execution but rather aim to find a balance between flexibility and quality.

It can be gleaned that a new mind set in the way quality tools are implemented in defence technology R & D project needs to be adopted. Rantanen and Domb (2002) advised that the old way of working used methods of Trial and Error, adding resources, hiding contradictions, finding a compromise (Trade Off analysis) in the designs and accidental iterations in the design evolution process. They recommended that the new efficient way of working looked at systematic methods, making use of available resources, finding the ideal design and defined patterns in the design evolution process. This is shown in Figure 2.1. Similarly, Smailagic and Smailagic (2014) added that complex activities in R & D projects require a systematic method to identify and visualise the flow of information rather than material. Therefore, this study aims to identify quality methods that make use of available resources and uses a systematic and logical approach to optimising defence technology R & D project execution that will deliver superior military technologies to the SANDF.

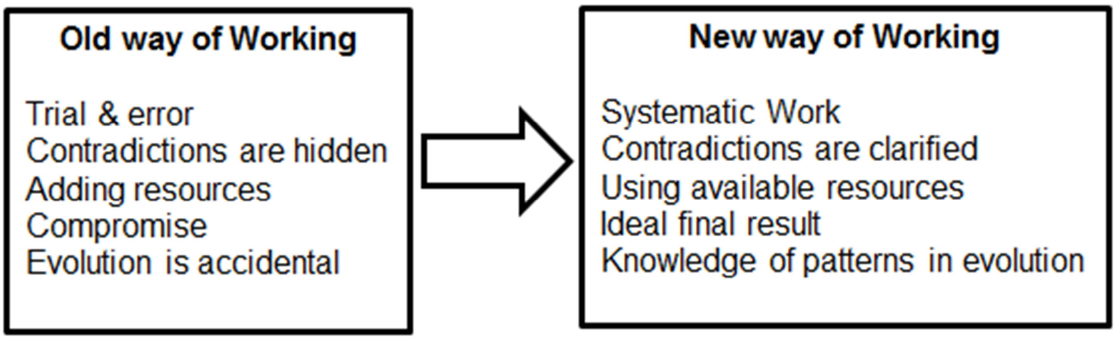


Figure 2.1 The transition from old way of thinking to the new way of thinking. (Source: Rantanen and Domb, 2002)

To conclude, it can be gleaned that quality methods to optimise defence technology R & D project execution should:

- Embrace the non-standard and non-repetitive nature of defence technology R & D project execution activities.
- Be flexible so that it can be incorporated into a framework in the form of a toolbox that contains a combination of useful methods extracted from proven systems such as Six Sigma.
- Use a systematic and logical approach to optimise defence technology R & D activities.

Based on the assessment of the preceding section, the next section will list various quality tools suitable for defence technology R & D project execution.

2.3 Quality tools for R & D Projects

This section will review various quality methods to optimise R & D activities that aim to deliver high quality technology concepts, as well as reducing project delays and the use of unplanned resources. The Guideline on defence technology R & D projects recommends that a flexible approach be adopted during the lower level execution process (Armscor, 2003). Therefore the selection of the quality tools was based on criteria identified in Section 2.2 in that it should be conducted systematically, logically laid out, simple and efficient to use, low cost, not burdensome in terms of more paperwork and embrace the flexible method of defence technology R & D project execution activities. Implementing the complete Six Sigma process may create rigidity, result in delays, and stifle the creativity of technology researchers leading to frustration. Instead various tools that comply with criteria in Section 2.2 were extracted from the Six Sigma philosophy and are discussed in this section. The following key methods will be reviewed:

- Quality Function Deployment,
- Axiomatic Design Method,
- TRIZ Inventive Problem Solving Method,
- Pugh Selection Matrix,
- Design Failure Mode Effect Analysis,
- Taguchi Robust Design Method

2.3.1 Quality Function Deployment (QFD)

In this section, the method of Quality Function Deployment (QFD) will be defined and discussed. The effectiveness of this tool in clearly interpreting functional requirements into technical (engineering) requirements will be explained as it is perceived in defence technology R & D project execution that technical requirements are not clearly defined at the beginning leading to review of these requirements during the development phase culminating in redesign activities.

Some of the current key issues that are perceived to be the cause of project delays and the use of scarce resources are the practice of continual review and adjustment of technical requirements within defence technology R & D project execution. According to Yang and El Haik (2003), the R & D project team should take the time to understand the customer needs and to plan the R & D project carefully so as to anticipate failures and avoid major downstream changes. Thompson (2015) highlighted that the influence of requirement changes may be the difference between successful delivery and the failure to complete the R & D projects on time and within budget. Quality Function Deployment is a tool that can be used to define technical requirements at the beginning of the R & D phase.

Alwerfalli and Lash (2012) defined QFD as a process of translating the Voice of the Customer (VOC) into technical requirements in ensuring that the customer needs are met. Cudney and Furterer (2012) concurred that it is vital to understand what is important to the customer and to interpret the customer's requirements into the technical requirements of the product to be designed. The defence technology R & D project team also needs to understand the SANDF requirements on future technology capability and translate these into clear technical requirements so as to design a product that meets their expectations.

According to Alwerfalli and Lash (2012), the House of Quality (HOQ) matrix is a useful tool in QFD to link technical requirements to the VOC. Figure 2.2 shows a HOQ matrix where technical requirements are referred to as design characteristics. Baxter (2015) stated that the House of Quality consists of six (6) steps:

- **Step 1**: Identifying customer requirements and ranking the requirements according to priority
- **Step 2:** Determining the current design benchmark against customer requirements
- **Step 3:** Designing characteristics intended to deliver customer requirements
- **Step 4**: Identifying the strength of the relationship between customer requirements and design characteristics
- **Step 5:** Determining correlations between each design characteristic
- **Step 6:** Finally, determining the design characteristic scores.

Baxter (2015) confirmed that customer requirements can be interpreted into clear design characteristics and prioritised systematically by applying these six steps. Translation and prioritisation of critical SANDF requirements into clear design requirements or technical requirements are necessary for the development of effective military technologies.

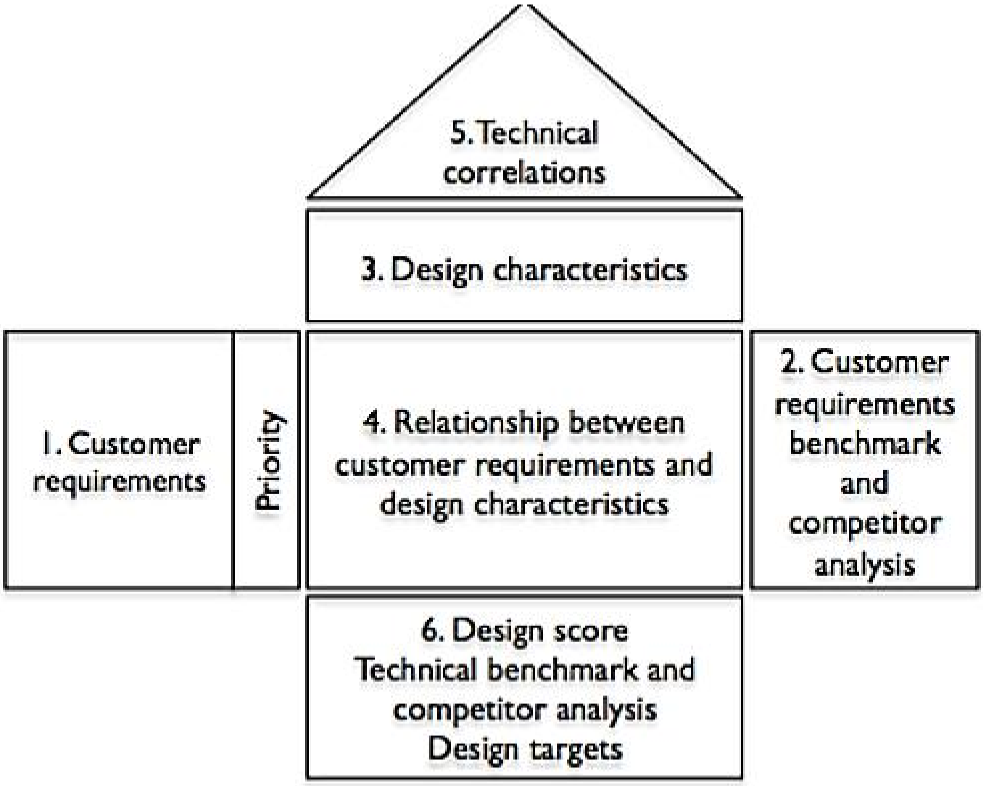


Figure 2.2 QFD House of Quality (Source: Baxter, 2015)

Cudney and Furterer (2012) cited Paryani et al. (2010) who stated that the advantage of using QFD can result in an improved understanding of customer requirements, higher levels of customer satisfaction and shorter development times and costs. Similarly, Yang and El Haik (2003) expressed that QFD provides the customers what they require which is quicker turnaround times and the prevention of failures and redesign. Shorter development cycles and the avoidance of redesign are key attributes that need to be identified during the execution of defence technology R & D projects as current quality methods are perceived to be creating project delays and redesign.

From the examination of literature on the QFD method, it is apparent that this method uses a logical systematic six step process to carefully translate the customer's functional requirements into technical and design requirements. Furthermore, it can be gathered that the use of QFD reduces R & D project timescales. Because QFD encourages technical and design requirements to be defined at the early stages of the technology R & D phase it will prevent late modifications (redesign) to the design. In contrast, it is assumed that current quality methods in defence technology R & D projects allow late technical requirement changes to occur resulting in further modifications to the design.

2.3.2 Axiomatic Design

This section discusses the method of Axiomatic Design. The systematic processes of this method in determining the quality of designs through design axioms are explained. The effectiveness of this tool in comparison to the Trade Off analysis and Trial and Error method which is assumed to be costly and time consuming is clarified.

According to Yang and El Haik (2003), Axiomatic Design is a simple and systematic method for analysing the quality of current concepts and novel designs through a thorough analysis of the customer's functional requirements. Banciu and Draghici (2003) agreed that Axiomatic Design optimises design activities by means of logical and rational processes and methods. Yang and El Haik (2003) stated that Axiomatic Design aimed to minimise the use of the Trial and Error method, speed up the R & D process and optimise quality and reliability of the designed product. In contrast, current quality methods in R & D projects such as Trial and Error experimental method requires back and forth redesigning of the concept that results in R & D project delays and the use of unplanned resources.

Banciu and Draghici (2003) added that although Axiomatic Design was specifically developed to optimise the design of mechanical systems, the method has been utilised in other sectors such as automotive, aerospace, process equipment, financial services, software services, software design and military application. Moreover, they also confirmed that although the Axiomatic Design method is effective when used throughout the entire R & D cycle, it also has the ability to be applied on specific sections of a design. Thus, it can be inferred that the flexibility of this tool makes it suitable to be incorporated into specific activities of defence technology R & D projects such as the lower level technical and design activities of project execution.

As reported by Rauch, Dallasega and Matt (2015), in Axiomatic Design the designer is guided by two important axioms and these axioms assist in evaluating and selecting designs in order to produce a robust design. They defined axiom 1 as:

- **The Independence Axiom**: When there are two or more functional requirements, the design solution must be such that each one of the functional requirements can be satisfied without affecting the other functional requirements.

Park (2007) explained that for Axiom 1, the axiom tells that a design parameter should be defined to independently satisfy one functional requirement. Suh (2001) elaborated further that in an acceptable design, a design parameter can be adjusted to satisfy its corresponding functional requirement without affecting the other functional requirements. He added that this ensures that functional requirements are independent of each other which guarantee an optimised robust design. The axiom 1 rule of axiomatic design minimises the effect of Trade Off analysis on a design by ensuring that changes to a specific characteristic have no negative impact on another characteristic. In contrast, the current quality method of Trade Off analysis method is used to optimise a quality characteristic, however, it meant the deterioration of another characteristic in the design. Hence by conforming to axiom 1 rule, a robust military design can be developed for the SANDF during the execution of defence technology R & D project without implementing the Trade Off analysis method.

The second axiom defined by Rauch, Dallasega and Matt (2015) is:

- **The Information Axiom**: Minimise the information content of the design. This implies that the design with the least amount of information is the best to achieve the functional requirements of the design.

Park (2007) explained that when many designs are found to conform to Axiom 1, the best one can be chosen based on Axiom 2 which is the best design that has minimum information content. He confirmed that the design with the minimum information content is selected as the final design. Hence, this implies that minimising the amount of information on a design would result in a simpler design, as well as reduced use of scarce resources. Within the defence technology R & D project execution environment where resources are limited, compliance to design Axiom 2 rule will ensure optimum use of these resources.

The axiomatic design process follows the Zig and Zag process where all functional requirements and design parameters of the design are identified by the decomposition process shown in Figure 2.3

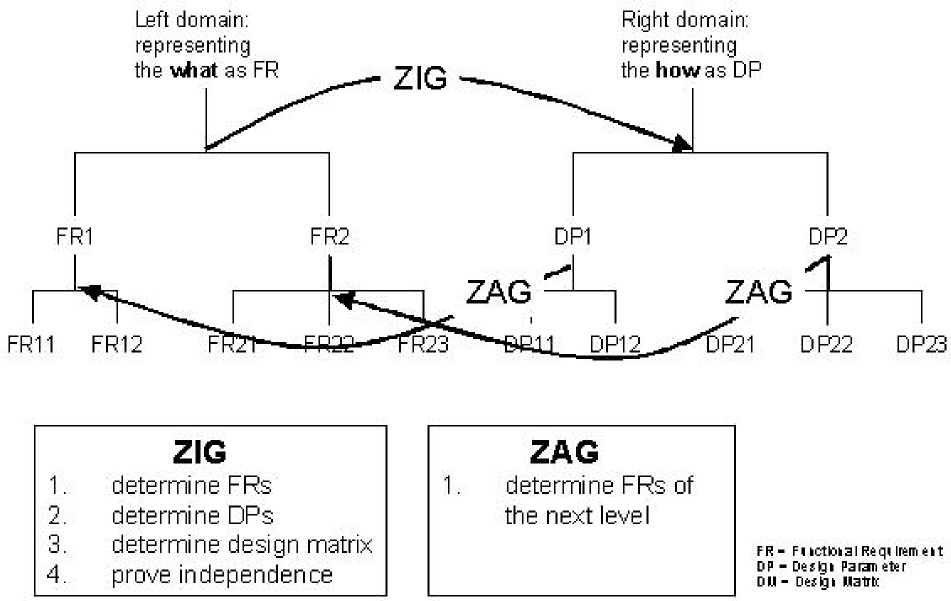


Figure 2.3 Decomposition Process of Axiomatic Design (Source: System Design, 2004)

According to Figure 2.3, the activities of Zig in listing the functional requirements and design parameters (requirements) are listed as follows:

a. **Determine the functional requirements and the design requirements**: Alwerfalli and Lash (2012) stated that the QFD can be used to define functional requirements (FR) to ensure the R & D project team have something to design towards. They further added that each functional requirement will have a specific design parameter (DP) that must be met.

b. **Determine the design matrix and determine independence of the functional requirements from one another**: Park (2007) defined three types of design matrices where the dependence between functional requirements and design parameters can be determined. He defined these as being uncoupled design, decoupled design and coupled design.

An uncoupled design matrix is illustrated in Figure 2.4 where the functional requirements are independent of each other. The independent relationships (A_{ij}) are diagonal as shown in Figure 2.4. Park (2007) explained that if the design matrix is a diagonal matrix, it is an uncoupled design because each design parameter can satisfy a corresponding functional requirement. Therefore, the uncoupled design perfectly satisfies the Independence Axiom 1. Yang and El Haik (2003) highlighted that uncoupled designs are desirable from controllability, quality and robustness standpoints and that has the potential for ease of production. Thus, the development of superior solutions during the defence technology R & D project execution should also follow the approach of an uncoupled design.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{pmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{23} \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad \begin{aligned} FR_1 &= A_{11}DP_1 \\ FR_2 &= A_{22}DP_2 \\ FR_3 &= A_{33}DP_3 \end{aligned}$$

Figure 2.4 Uncoupled Design Matrix (Source: Suh, 2001)

The next design matrix that a design can conform to is a decoupled design. When the dependent relationship is triangular as shown in Figure 2.5, the design is a decoupled design (Suh, 2001).

As clarified by Suh (2001) there are designs with some dependence among their functional requirements, but the dependencies are minimal. Hence, the development of superior military technologies for the SANDF during the execution of Defence technology R & D project could also follow the approach of a decoupled design where dependence to some of the adjacent functional requirements can be minimised.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} \\ 0 & A_{22} & A_{23} \\ 0 & 0 & A_{33} \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad \begin{aligned} FR_1 &= A_{11}DP_1 + A_{12}DP_2 + A_{13}DP_3 \\ FR_2 &= A_{22}DP_2 + A_{23}DP_3 \\ FR_3 &= A_{33}DP_3 \end{aligned}$$

Figure 2.5 Decoupled Design Matrix (Source: Suh, 2001)

The third design matrix that a design can follow is a coupled design. According to Park (2007) when a design matrix is neither diagonal nor triangular, the design becomes a coupled design. In a coupled design, no sequence of design parameters can satisfy the functional requirements independently. This phenomenon is shown in Figure 2.6. He added that a coupled design does not conform to design Axiom 1. This implies that if any functional requirement is changed, the characteristic of all the other functional requirements may be negatively affected. Similarly, the Trade Off analysis method follows a coupled design approach in developing a design. Thus, a coupled design is not a suitable design as it is vulnerable to design changes making it a weak design. Thus, a weak coupled military design that is vulnerable to various types of threats in war is definitely not suitable for the SANDF where South African soldiers' lives are at risk.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad \begin{aligned} FR_1 &= A_{11}DP_1 + A_{12}DP_2 + A_{13}DP_3 \\ FR_2 &= A_{21}DP_1 + A_{22}DP_2 + A_{23}DP_3 \\ FR_3 &= A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3 \end{aligned}$$

Figure 2.6 Coupled Design Matrix (Source: Suh, 2001)

Of particular importance, axiomatic design processes also allow a coupled design to be simplified into an uncoupled or decoupled design. This means that a weak design can be optimised to a robust design. Yang and El Haik (2003) stated that a coupled design results when the matrix has the number of requirements greater than the number of design parameters. They advised that a coupled design may be uncoupled or decoupled by smartly adding extra design parameters to the structure by using axiomatic design theorems and corollaries. These theorems and corollaries are listed in Annexure A. Banciu and Draghici (2003) stated that these theorems and corollaries which are based on the design axioms can be used as design rules to optimise a design. Therefore the axiomatic design process provides a logical method of solving weak coupled designs through the use of these theorems and corollaries. Alternatively, as reported by Yang and El Haik (2003), synergy can be gained between Axiomatic Design and the Theory of Inventive Problem Solving (TRIZ) where the TRIZ contradiction elimination principles can be used to reduce or eliminate coupling weaknesses.

Once the Zig activities on the higher level have been completed in the decomposition process, the next step is to Zag to the lower level functional requirements as shown in Figure 2.3. The Zig and Zag processes are repeated to the lowest level of the design. Yang and El Haik (2003) explained that the process of Zig and Zag must continue until no further decomposition can be done such as when material properties or geometric dimensions of the design are reached. Hence, a thorough analysis of the critical functional and design requirements of the design can be determined using the Zig and Zag method. This method suggests that all crucial design characteristics of a SANDF military concepts are identified on paper before full scale development and testing commences during the defence technology R & D project execution.

Rodríguez and Benavides (2014) emphasise that the main benefit of an axiomatic design is the drastic reduction in time through the analysis of the design to compliance with the two axioms. They further indicated that potential improvements to the design are immediately identified without the high use of iterative analytical methods. Therefore iterative methods such as Trial and Error and Trade Off analysis can be replaced with the use of the axiomatic design method. Another useful benefit of Axiomatic Design method is its beneficial relationship with QFD to define technical requirements and TRIZ in solving design couplings.

From the review of documentation on the Axiomatic Design Method, it has been confirmed that this method is a simple and systematic tool for optimising designs by providing the project team with a theoretical foundation based on logical and rational processes. Moreover, Axiomatic Design aimed to minimise the use of Trial and Error and Trade Off analysis methods which are perceived to be inefficient. The review further highlighted the flexibility of the Axiomatic design method where it can be applied to military projects and lower technical aspects of technology R & D projects. Hence this makes Axiomatic design method a suitable quality tool to optimise design methods of defence technology R & D project execution.

2.3.3 TRIZ Inventive Problem Solving

This section describes the method of TRIZ Inventive Principles. The techniques developed to resolve technical and physical contradictions in designs are explained.

The effectiveness of this tool is in contrast to Trade Off analysis and Trial and Error method which are perceived to be inefficient is revealed.

According to Yang and Zhang (2000), TRIZ is the Russian acronym for The Theory of Inventive Problem Solving that originated from extensive studies of technical and patent information of designs. Ilevbare, Phaal, Probert and Padilla (2011) reported that TRIZ founder Genrich Altshuller studied 400,000 technology R & D patents and from them identified basic patterns which governed the process of solving problems and creating new ideas. Yang & Zhang (2000) stated that to generate these ideas, TRIZ provides techniques and methods to help R & D project teams create new designs and avoid numerous Trial and Errors during the problem solving process. Mehta (2014) agrees that for defence R & D projects there is neither room for wasteful timescales nor Trial and Error testing as the delivery of successful results to the customer is becoming increasingly high.

Ilevbare et al. (2011) outlined that this systematic method of TRIZ offers a comprehensive toolkit with a simple method for understanding problems and provides detailed techniques for design analysis to arrive at solutions. Yang and El Haik (2003) confirmed that TRIZ developed a system of methods to define and solve problems and consists of the following activities:

- Problem definition
- Problem classification and tool selection
- Solution generation and Concept evaluation.

The first step is to define the quality problem that may affect the function of the design using the functional modelling as shown in Figure 2.7. Yang and El Haik (2003) stated that Functional modelling and analysis may be used to identify the problem more clearly and precisely. Ilevbare et al. (2011) concurred that a Function analysis helps to identify difficult issues that may affect the quality of the design. Yang and El Haik (2003) commented that three elements are needed to deliver a function which is a subject, a field and an object. They defined these activities as, where:

- the subject is the source of action,
- the object is the action receiver and

- the action is the verb in a functional statement and it is represented by an arrow.

Ilevbare et al. (2011) defined the action as any influence that causes the object to change which can be a normal, harmful or an insufficient action. Yang and El Haik (2003) emphasised that actions are delivered by various fields such as physical, chemical and geometric properties of substances and knowledge in these areas are important in developing superior technical systems. Thus the R & D project team needs to have research engineers and scientists with adequate knowledge of scientific principles on physical, chemical and geometric properties of substances and fields.

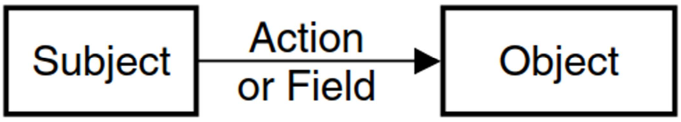


Figure 2.7 Function Modelling (Source: Yang and El Haik,2003)

Once the problems (harmful actions) have been identified, the next step is to classify the problem and select the appropriate tool to solve the contradiction. According to Yang and El Haik (2003), a problem can be classified as either a technical contradiction or physical contradiction. Ilevbare et al. (2011) defined a technical contradiction as the ability of a technology to carry a function while the other functions are harmfully affected. This can occur as a result of Trade Off analysis. Shiu, Yang and Tu (2013) highlighted that the disadvantage of Trade Off analysis is the frequently seen situation where the improvement of a quality characteristic may cause the deterioration of another quality characteristic. Yang and El Haik (2003) agreed that the problem associated with solutions generated through Trade Off analysis is that it does not eliminate the technical contradictions, but rather softens them, thus retaining the harmful action in the system. This further substantiates that the method of Trade Off analysis to optimise designs is not efficient. Hence, this study will identify alternative quality tools that are able to eliminate technical contradictions in designs generated during defence technology R & D project execution.

Yang and El Haik (2003) stated that the inventor of the TRIZ process, Genrich Altshuller analysed more than 400,000 R & D patents and identified about 1250 typical technical contradictions. They mentioned that Altshuller expressed these into a matrix of 39 x 39 engineering parameters. This contradiction matrix is shown in Annexure B. Yang and El Haik (2003) added that to resolve these contradictions, Altshuller compiled 40 principles. These 40 principles are listed in Annexure C. Caluyo (2014) indicated that a brainstorming tool is commonly used with a contradiction tool. Altshuller (2007) explained that in the Trial and Error method, in order to get to the solution, the R & D project team develops numerous searching concepts and begins to approach the problem in various directions thus consuming valuable time and resources. Whereas TRIZ, Yang and El Haik (2003) mentioned that the contradiction table and the 40 principles suggest the most promising direction for searching for a solution to optimise a design. Using the contradiction table and the 40 principles allows the R & D project team to move in a defined direction rather than moving in all directions hence saving time and resources.

The contradiction may also be written as a physical contradiction. Yang and El Haik (2003) defined a physical contradiction as a situation in which a subject or an object has to be in two mutually exclusive physical states such as a vehicle must be lightweight for better fuel economy and at the same time heavyweight for stability. As reported by Caluyo (2014), TRIZ aimed to remove the physical contradiction by splitting the two contradictory requirements. Hence Yang and El Haik (2003) introduced the separation principles for resolving the physical contradiction as follows:

a. **Separation in space:** This meant one section of a design has a function, while another separate section has an opposite function.
b. **Separation in time:** This meant that at one time period a design concept has a certain role and at another time period it has a contradicting role.
c. **Separation between parts:** Separation between the parts implies that one part has a specific purpose, while another part is given an opposite purpose.
d. **Separation between parts and a collection of parts:** Every single developed part must have a unique role but when the entire collection of parts are synchronised, they will provide a different role.

In addition to the method mentioned above, the TRIZ method provides additional methods to simplify a design. Yang and El Haik (2003) recommended using the trimming and pruning method to remove redundant components, thus simplifying the design. Gadd (2011) agreed that trimming increases benefits, reduces cost and harmful actions of the system by eliminating troublesome components and reduces the complexity of the design. Furthermore, Yang and El Haik (2003) stated that by reducing the need for redundant components in a design will decrease the cost and complexity of the design and hence result in less potential problems with the design. Hence a more superior design which is reliable can be generated through the trimming process. Once the correct tool has been selected various solutions can be generated using these methods of contradiction matrix, 40 principles, separation principles or trimming. According to Yang and El Haik (2003), several design concepts can be developed and these will need to be evaluated in order to make a sound final decision on which concept will be used. They explained that several methods can be applied in selecting the final design concept, including the Pugh Concept Selection technique, Design Reviews and Failure Mode and Effect Analysis (FMEA).

From the review of literature on TRIZ, authors have confirmed that this method provides systematic techniques for the R & D project team to create new designs and avoid numerous Trial and Errors during the problem solving process. Moreover, it negates the need for Trade Off analysis to optimise designs by offering a comprehensive toolkit of functional modelling, contradiction matrix, separation principles and trimming for understanding problems, as well as finding optimum design solutions. Significantly, the TRIZ method provides a cost effective approach to current quality methods in optimising designs on R & D projects. Thus, the TRIZ method has the tools to optimise designs during defence technology R & D project execution, therefore, it can be deemed as a suitable candidate to be included into a quality toolbox framework.

2.3.4 Pugh Selection Matrix

The preceding section mentioned that TRIZ may generate multiple design concepts and these will need to be evaluated in order to make a sound final decision on which concept will be used. This section describes the Pugh Selection Matrix Method. The step by step process involved in evaluating (comparing) multiple designs is described. The efficiency of this tool as a cost effective and quick method to choose the best design is explained.

Alwerfalli and Lash (2012) indicated that once various design concepts are generated, the designs are then sorted using a Pugh matrix to determine the best design to develop further. According to Lugo (2012), the Pugh selection matrix method guides the R & D team in generating suitable design decisions by creating an evaluation process to select the optimum design from other designs. Yang and Haik (2003) also acknowledged that the R & D project team should choose the best design concept using the Pugh concept selection method. Burge (2009) stated that the Pugh selection matrix provides a simple approach that evaluates multiple factors on each design when reaching a decision of selecting the best design. He further recognised that the Pugh selection matrix also permits for simple sensitivity analysis to be conducted on the various designs by an experienced R & D project team, thereby providing some information as to the robustness of a particular decision. Alwerfalli and Lash (2012) explained that the Pugh matrix may rate the design concepts based on cost, complexity, function, ease of implementation and quality. Hence, factors of cost, complexity, function, ease of implementation and quality are also critical in ensuring that superior military technologies are developed effectively, efficiently and economically for the SANDF during the execution of defence technology R & D projects.

The Pugh Selection Matrix follows a systematic process of six steps in determining the best design. These steps are:

a. **Identify the criteria for selection of the best design**: As reported by Burge (2009) the technical requirements can be used as criteria in selecting the best design. He emphasised that the technical requirements should stem from the customer requirements. QFD tool and Axiomatic Design methods are useful methods in defining functional and technical requirements. Yang & El Haik (2003) advised that the criteria selected should be agreed upon by members of the project team. Within the defence technology R & D project environment, this would imply that SANDF Project Officers, Project managers, Researchers and technical support should be involved in selecting the criteria for determining the best design.

b. **Select a concept as a baseline (Datum):** According to Cudney and Furterer (2012), one of the designs is selected as the candidate design to which other designs are compared with. Yang and Haik (2003) indicated that a datum design needs to be chosen with which all other concepts are to be compared. They further emphasised that the datum can be an existing design. Burge (2009) agreed that the previous design can be used as the baseline because it exists and its performance should be well known. Within the defence technology R & D project execution environment a baseline design may also include the current design or previous design which needs to be optimised.

c. **Compare candidate designs to Baseline Design**: Burge (2009) stated that each candidate design must be compared against the baseline design, requirement by requirement and a score allocated using the following point system:

S = same as
+ = better than
- = worse than

Cudney and Furterer (2012) indicated that if the new design concept is superior to the baseline design for a specific criterion, a plus sign (+) should be added in the block where the new design concept intersects the criteria and if the new design concept is less superior than the baseline design concept for a specific criterion, then a minus sign (–) should be added in the relevant block. However, they stated that if the new design concept scores the same as the baseline design on a specific criterion, then either a zero (0) or S for same is placed in the relevant block. This process is shown in Figure 2.8

	Concepts						
Criteria	1	2	3	4	5	6	7
A	–	–	–	0	Candidate	0	–
B	–	0	–	–	Concept	0	–
C	+	+	–	–		–	–
D	+	–	–	+		–	+
E	+	+	–	–		–	–
Pluses	3	2	0	1		0	1
Minuses	2	2	5	3		3	4
Zeros	0	1	0	1		2	0

Figure 2.8 Pugh Selection Matrix (Source: **Cudney and Furterer, 2012)**

d. **Score each candidate design**: Burge (2009) confirmed that for each design concept, the total score can be calculated by adding the number of +'s and –'s. Similarly, Yang and El Haik (2003) stated that certain design concepts will display strengths, while others will reveal weaknesses and the best design with the maximum number of + signs and minimum number of - signs should be chosen. However, if no clear winner can be determined from the above scoring, then the next alternative is to determine a hybrid design.

e. **Determine a hybrid design:** Burge (2009) suggested that a hybrid design can be determined by combining the best properties from each alternative design. Similarly, Cudeney and Furterer (2012) added that designs with the + can be used to form a hybrid design that takes the best characteristics of each design concept and consolidates them to form a superior concept.

Yang and El Haik (2003) raised the concern with regards to design coupling and contradictions that may occur when combining design characteristics. Axiomatic design method has the ability to resolve coupling between characteristics and TRIZ inventive principles may resolve technical and physical contradiction between characteristics.

It can be gleaned from literature on Pugh Selection to evaluate designs, that this method follows a simple logical process to assess multiple designs. The substitution of numerous experiments with a simple matrix exercise to evaluate multiple designs ensures that costs are maintained. Furthermore, the hybrid designs identified during the Pugh selection Matrix can be optimised using either the Axiomatic design or TRIZ methods which highlight synergy between these methods.

2.3.5 Design Failure Mode Effect Analysis (DFMEA)

This section presents the method of Design Failure Mode Effect Analysis (DFMEA). This method was developed to evaluate potential failures in designs early during development. The steps required to proactively mitigate these potential failures is revealed.

Cudney and Furterer (2012) defined Failure Mode Effect Analysis (FMEA) as a systemised method to evaluate the potential failure of a design and, thereafter, identify actions that could eliminate or reduce the potential failure from occurring. Yang and El Haik (2003) agreed that the FMEA method can help the R & D project team to improve the design and its R & D activities by asking what can go wrong and thereafter R & D activities are revised to reduce variation, as well as prevent the occurrence of failure modes. Similarly, Cudney and Furterer (2012) mentioned that FMEA is a great tool to identify the potential risks where design failures could occur. Thus, FMEA has the potential to identify potential failures early in the R & D project phase and therefore reduce the need for corrective action activities eventually minimising R & D project delays and the use of additional resources. Corrective action is currently recommended during the execution of defence technology R & D projects to resolve any quality problems with designs.

Design FMEA (DFMEA) are typically used to evaluate potential failures of designs. Maxim Integrated (2016) mentioned that Design Failure Mode and Effects Analysis (DFMEA) is a method for evaluating a design for robustness against potential failures. Yang and El Haik (2003) advised that to get the most out of DFMEA is when the failure modes are proactively recognised during the early stages of the R & D project when the design is still on paper. Contrary to this, the traditional quality methods of inspection are traditionally applied late in defence technology R & D project execution that is upon completion of a design.

The Design FMEA method makes use of the worksheet shown in Table 2.1. The worksheet is populated using the following steps:

Table 2.1 FMEA Worksheet (Source: Yang and El Haik, 2003)

FR, DP, or Process Step	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended
1	2	3	4	5	6	7	8	9	10
			0		0		0	0	
			0		0		0	0	
			0		0		0	0	
			0		0		0	0	
			0		0		0	0	

a. **Identify Functional requirements and design parameters**: According to Yang and El Haik (2003) Functional requirements (FR) and Design parameters (DP) for Column 1 in Table 2.1 can be effectively obtained from the zig and zag process during the Axiomatic design method.

b. **Identify potential failure modes:** Yang and El Haik (2003) stated that the project team should identify all potential failure modes that may cause the design to fail to perform its functional requirements. They categorized failure modes occurring in material, environment, people, equipment and methods. Raytheon (2007) mentioned that for each functional requirement the team brainstorms all potential failure modes that would prevent the design from failing to satisfy each functional requirement. The Mind Tool Limited (2009) stated that brainstorming is a popular tool to generate creative solutions to solve a problem. The Mind Tool Limited (2009) further emphasised that when brainstorming is used in a team method, it brings the diverse experience of all team members into play which increases the opportunity to find better solutions. Likewise, within the defence technology R & D project execution, various solutions can be generated by the R & D project team comprising of SANDF R & D officers, Project Managers, Research engineers and scientists.

According to the Mind Tool Limited (2009), the following is required to ensure an effective brainstorming session:

- Define the problem that needs to be solved clearly and lay out any criteria to be met. The objective is to generate as many ideas as possible.
- Provide ample time for each team member at the start of the session to generate as many ideas as possible.
- Allow each team member to share their ideas fairly.
- Encourage members to adapt fellow members' ideas to create better ideas.
- Ensure no criticism occurs as this can stifle creativity and cripple the free running nature of a good brainstorming session.
- Ensure that no train of thought is followed for too long.

c. **Determine Potential Failure Effects and Causes:** Yang and El Haik (2003) indicated the causes of potential failures are generally noise factors (uncontrollable factors). As stated by Unal and Dean (1991) noise factors are those factors which are uncontrollable and can include variations in environmental (external) operating conditions or deterioration of components in a product during application. A block diagram can be used to identify noise factors and its interaction with design parameters, controlled inputs and functional requirements as shown in Figure 2.9. Raytheon (2007) asserted that the interfaces in a block diagram include controlled inputs such as design parameters, uncontrolled inputs such as noise factors and outputs such as functional requirements.

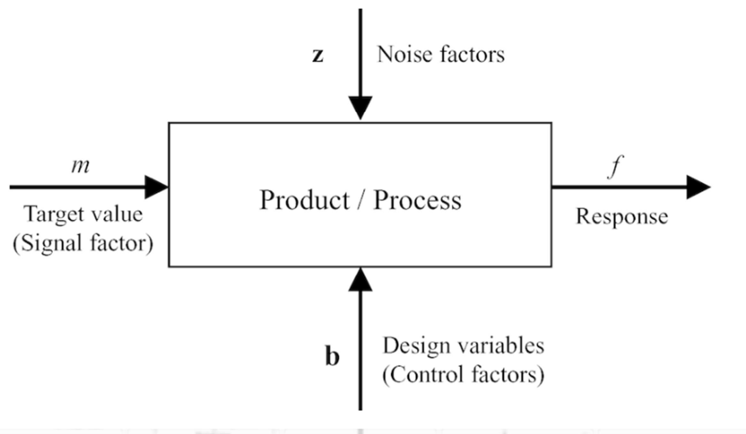


Figure 2.9 Block/P Diagram (Source: Park et al. 2006)

Alternatively, potential failures can also be identified using a Cause and Effect Diagram. Levine, Ramsey and Smidt (2001) mentioned that the Cause and Effect diagram illustrates the relationship between an effect (problem) and a set of possible causes that produce the effect. This is shown in Figure 2.10 where the effect can be a problem where the major causes are listed on the left hand side of the diagram. According to Usmani (2014), major causes of effects could originate from Material, Methods and Processes, Machine and Equipment, Manpower, Measurement Devices and Environment.

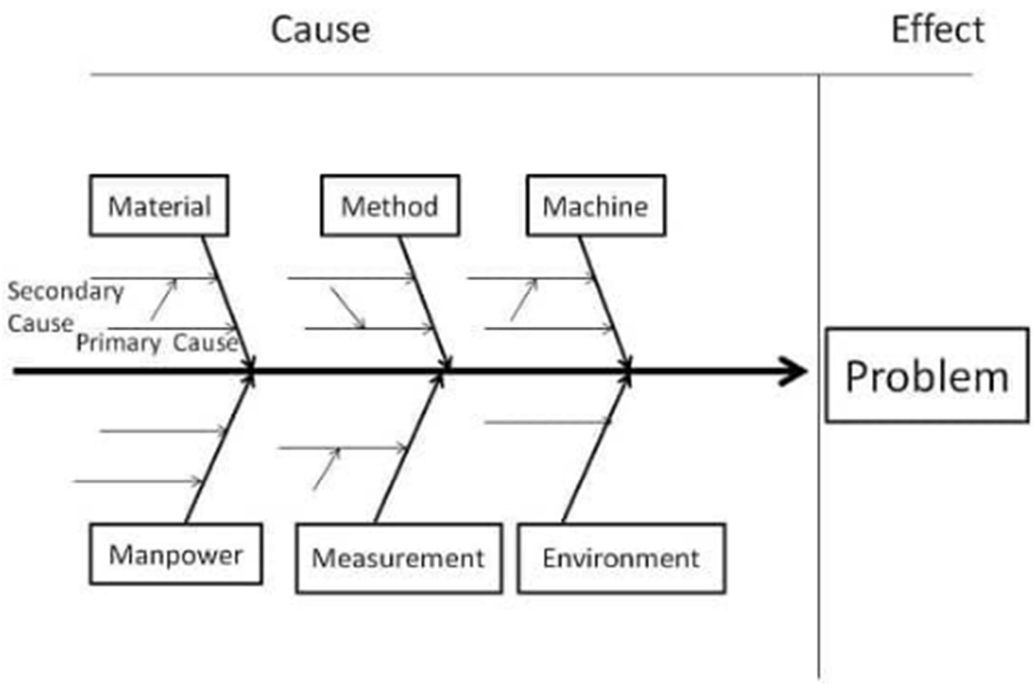


Figure 2.10 Cause and Effect Diagram (Source: Usmani, 2014)

d. **Rank Severity of Potential Failure Effects**: Yang and El Haik (2003) expressed severity as a subjective value of how serious the influence of the failure mode is to the design. They expressed that the severity is rated on a scale from 1 which implies no effect to 10 which can mean hazardous effect as defined in Annexure D.

e. **Determine the Occurrence of Potential Causes:** According to Yang and El Haik (2003) occurrence is the probability of the event occurring and occurrence is rated on a scale of 1 (almost never) to 10 (almost certain) (Refer to Annexure D).

f. **Determine Design Controls:** Yang and El Haik (2003) confirmed that in DFMEA, design controls ensure the prevention or reduction of the causes of failure modes by identifying and detecting the design vulnerabilities (deficiencies) as early as possible. Contrary to this, current quality practices in defence technology R & D projects recommend quality controlling upon completion of deliverables which means that design vulnerabilities are only identified after completion and evaluation of a design through tests and experiments.

   Yang and El Haik (2003) listed various methods to detect design deficiencies such as project and design reviews, design modelling and tests.

g. **Determine the likelihood that a Potential Failure Mode can be detected**: According to Yang and El Haik (2003) detection is a subjective score corresponding to the probability that the detection method will identify the failure of a potential failure mode. They further noted that the project team should evaluate the effectiveness of each detection control method and rate the effectiveness of the method. The rating values for the control methods can be determined from the table in Annexure D.

h. **Prioritise the Risk**: Yang and El Haik (2003) mentioned that the severity of the risk known as the Risk Priority Number (RPN) is the product of severity, occurrence and detection ratings. Risk Priority Number (RPN) is calculated as follows:

   RPN = SEVERITY x OCCURRENCE x DETECTION

   Yang and El Haik (2003) indicated that the RPN values are used to prioritise potential failures that may occur. Thus, rather than conducting numerous Trial and Error experiments with cost implications, potential failure causes can be identified early by merely conducting a paper study through DFMEA.

i. **Recommended Actions to Reduce Failure**: Sellappan (2013) stated that actions are a way to reduce the risk of failure modes. Yang and El Haik (2003) agreed that where the risk of potential failures is high, an immediate control plan should be drafted to control the situation. Raytheon (2007) listed several design control methods that can be used to reduce the risk of failure modes that include simulation, the design of experiments and robust parameter design. According to Ghani et al. (2013), the robust parameter design method of Taguchi has become an effective tool in solving problems and optimising products and process designs.

From the examination of literature on DFMEA, it is noticeable that this systematic method proactively identifies failures during the early stages of the design when it is still on paper. Whereas current quality methods are conducted late in the R & D phase that is upon completion of deliverables and thus this creates the need for further redesign of the concept. Literature revealed that once DFMEA has identified potential problems with designs, it creates an action plan to reduce these failures that recommends appropriate methods such as simulation and robust parameter design method of Taguchi to resolve these design problems. With its logical approach and low cost to implement, DFMEA has the potential to be included in the framework to be developed for defence technology R & D project execution.

2.3.6 Taguchi Robust Design Method

This section describes the low cost and shorter fractional factorial experimental method of Taguchi Robust Design to optimise designs. The logical approach that is used to thoroughly analyse the design against various design parameters is shown.

According to Telford (2007) Design of Experiments (DOE) is a structured and organised way of conducting and analysing controlled tests to evaluate the factors. These factors are referred to as controlled and uncontrolled factors that affect the response variable (output value) which is illustrated using the P diagram shown in Figure 2.8.

Yank and El Haik (2003) stated that there are two main types of DOE strategies which are represented as full factorial and fractional factorial designs. However, they cautioned that a full factorial design of experiment can acquire more data from the test, but the downside with this method is that the test size will grow substantially with the higher number of experiment factors and levels. Oehlert (2010) emphasised that a full factorial DOE may be wasteful or unfeasible if resources are limited.

Ghani, Jamaluddin, Rahman and Deros (2013) confirmed that many organisations are not able to use full factorial DOE to develop a quality product with reduced manufacturing cost and a shorter development process. They reasoned that the traditional full factorial DOE is known to be very complex and expensive which requires capable resources for successful implementation. Yank and El Haik (2003) agree that although full factorial DOE will provide more information; it will require more experimental runs which are costly. Furthermore, Ghani et al. (2013) cited Nalbant et al. (2007) who admitted that full factorial DOE becomes difficult to use when a large number of experiments have to be conducted as the number of test parameters increase. Hence, they admitted that the Trial and Error experimental method is still a popular approach to be employed rather than the full factorial DOE. Therefore, this method of full factorial DOE might also not be suitable for defence technology R & D projects execution where resources are limited as the objective of this study is to find efficient quality tools to reduce project delays and unplanned resource utilisation.

As reported by Levine et al. (2001), when four or more factors are to be evaluated, often the experiment becomes costly or impossible to simultaneously run all treatment combinations. Hence, a more economical way of testing the treatment combinations should be used so that the experiment can achieve meaningful results. Yang and El Haik (2003) indicated that fractional DOE is intended to significantly lower the number of experimental runs and to use the information acquired from the experiments more wisely. Montgomery (2013) confirmed that fractional DOE is amongst the most popular cost effective methods for product and process design optimisation. Goode (1999) stated that a common replacement to the full factorial DOE is the fractional DOE method called the Taguchi Robust Design technique. Ghani et al. (2013) confirmed that the Taguchi Robust Design method has become an alternative in solving problems and optimising products and process design. They highlighted that Taguchi Robust Design's simplicity in data collection and reduced experimental time and cost, makes this tool useful to any organization. Likewise Unal and Dean (1991) cited Cullen and Hollingum (1987), Logothetis and Salmon (1988), Sullivan (1987) and Wille (1990) who all stated that the quality engineering method of Taguchi Robust Design is one of the most significant methods for evaluating the quality of designs at reduced cost. Thus, the low cost and ease of use allow the Taguchi Robust Design method to be incorporated into a quality toolbox framework for defence technology R & D project execution. Ghani et al. (2013) added that Taguchi Robust Design method provide an efficient and systematic approach to optimise designs for performance, quality and cost. Simpson (2000) stated that the inventor of the method, Taguchi was quick to highlight that no amount of quality inspection can optimise a product and that quality must be designed into a product from the start. Hence, this thinking is contrary to the current quality methods in defence technology R & D projects where quality inspection is conducted only at the completion of deliverables.

The Taguchi Robust Design method provides an efficient and systematic way to optimise designs and hence the following steps are conducted to ensure this:

a. **Determine the Quality Characteristic:** The initial step in the Taguchi Robust Design method according to Unal and Dean (1991) is to identify the quality characteristic to be improved. Goode (1999) added that the quality characteristic is the parameter that will be measured to the determine success or failure of the design. Unal and Dean (1991) provided examples of quality characteristics such as weight, cost, corrosion, target thickness, strength of a structure and electromagnetic radiation.

b. **Identify the Noise Factors**: Shiu et al. (2013) defined uncontrollable factors as noise factors which cause variability in designs. Unal and Dean (1991) stated noise factors are uncontrolled environmental elements that the product is exposed to during operational use that may cause deterioration of components within a product. Levine et al. (2001) confirmed that the noise factors are environmental and represent conditions under which the design is expected to perform. Noise factors can be identified using the P diagram tool as shown in Figure 2.9.

c. **Identify the Control Parameters or Factors:** This step is to identify the control factors that have notable influence on the quality characteristic. Rekab and Shaikh (2005) stated that control factors are those design factors that can be set and maintained. Simpson (2000) provided examples of control which can easily be measured and monitored, such as material choice and cycle time. The controlled factors can be identified using the P Diagram tool as shown in Figure

2.9. Simpson (2000) added that the design method aims to identify different settings of control factors which ensure that the design is insensitive to variations in noise factors, thus making the design more robust. Levine et al. (2001) suggested that subjecting the design parameters to a variety of environmental conditions should result in a design that is insensitive to a variety of environmental conditions.

d. **Design the Matrix Experiment**: The next step is to design the matrix experiment. Unal and Dean (1991) stated that the objective of the matrix is to choose the best combination of control parameters so that the product or process is most robust with regards to noise parameters. The Taguchi Robust Design method utilises orthogonal arrays (OA) from the full design of experiments method to evaluate a large number of variables with a small number of experimental runs. Goode (1999) confirmed that the use of orthogonal arrays as a tool enables the researcher to test only a portion of the possible test combinations of variables using a defined pattern and this method produces results more efficiently and economically than a full design of experiments approach. This method may prove effective in reducing project delays and the use of unplanned resources.

Phadke (1989) advised that evaluating the design parameters one at a time or by Trial and Error until an acceptable design is established is a popular method to optimise the design. Ghani et al. (2013) agreed that the Trial and Error experimental method is still a popular approach to be employed. However, Phadke (1989) cautioned that Trial and Error results in a very lengthy and costly process for completing the design or it may result in a premature closure of the design process due to budget or schedule pressures culminating in a less optimal product design. Contrary to this, Taguchi Robust Design method allows the control and noise parameters simultaneously to be evaluated using the Orthogonal Array matrix shown in Figure 2.11. Shiu et al. (2013) indicated that Orthogonal Arrays test the interaction of both control factors and noise factors. This is revealed in Figure 2.11 where the matrix tests the control factors and uncontrolled factors simultaneously with the results of the experiment for each combination of control and noise array experiment being denoted as $Y_{i,j.}$

Noise Orthogonal Array

	1	2	3	4
N1	1	1	2	2
N2	1	2	1	2
N3	1	2	2	1

Control Orthogonal Array

	A	B	C	D	Y i,j				Mean	Std
1	1	1	1	1						
2	1	2	2	2						
3	1	3	3	3						
4	2	1	2	3						
5	2	2	3	1						
6	2	3	1	2						
7	3	1	3	2						
8	3	2	1	3						
9	3	3	2	1						

Figure 2.11 Orthogonal arrays with control and noise arrays (Source: Unal and Dean, 1991)

e. **Analyse the Data:** After the experiments have been conducted, the data must be analysed. As reported by Levine (2001) to evaluate treatment combinations that take the average value for a particular treatment combination and its standard deviation, the signal-to-noise (S/N) ratio is used. Figure 2.11 shows the matrix with values for $Y_{i,j}$, a mean and standard deviation that is required to calculate the S/N ratio. According to Simpson (2000), there are three standard types of S/N ratios that can be calculated depending on the desired performance response of the design. These being:

- Smaller the better (for making the system response as small as possible): SN_S
- Nominal the best (for reducing variability around a target): SN_T
- Larger the better (for making the system response as large as possible): SN_L

From the review of literature on Taguchi Robust Design Method, it is apparent that the Taguchi method is a systematic and efficient method for optimising an experimental configuration. Unlike the Trial and Error experimental method that is time consuming and is expensive since experiments are conducted one at a time to test parameters, Taguchi Robust Design method allows the control and noise parameters to be evaluated simultaneously using the Orthogonal Array matrix. Hence, the Taguchi Robust design method seeks to design a technology which is robust to the causes of quality problems with the added benefit of considerable time and resource saving. Hence, a method such as Taguchi Robust Design Method will ensure project delays and use of unplanned resources are minimised within Defence technology R & D project execution.

2.4 Summary of chapter

Literature confirmed that quality methods for R & D projects like defence technology R & D projects should be conducted systematically, logically laid out, simple and efficient to use, low cost, not burdensome in terms of more paperwork and embrace the flexible method of defence technology R & D project execution activities. Based on these criteria, various quality tools were identified. A review of these quality tools revealed the following findings:

- The majority of these tools such as QFD and DFMEA can be applied early during the defence technology R & D project execution before the technology concept is developed and evaluated thus saving time and cost. In contrast, current quality methods such as post deliverable quality inspections are conducted late in the execution phase and hence create the need for further redesign or corrective action of the concept. Furthermore no amount of quality inspection can optimise a technology concept rather quality must be designed into a product from the start.
- The tools provide a suitable alternative to the lengthy and costly methods of Trade Off analysis, Trial and Error, multiple comparative testing, large sample size testing.
- Each tool may be applied on its own or combined with one or more tools during evaluations such as QFD with Axiomatic design or TRIZ Inventive problem solving. Thus this review revealed the modular characteristics (flexibility) of these tools.
- An examination of the various steps in the quality tools exposed the use of other embedded methods that aid in the successful implementation of the quality tool. Embedded methods such as design reviews, Ishikawa cause and effect, P-diagram, Brainstorming were identified.
- The embedded methods listed above supported more than one quality tool such as P-diagram and it was applied in Taguchi Robust design and DFMEA tools.
- The embedded tools such as P-diagram, Ishikawa cause and effect and Brainstorming have autonomy to be applied as a tool on its own. Hence, showing the flexibility of these methods to be included into a quality toolbox.

Based on the findings mentioned above, the quality tools and the embedded methods form mutual relationships as illustrated in Figure 2.12. This figure illustrated various connections amongst all the methods as identified during the review of the literature. However though symbiotic relationships were identified amongst these quality methods as shown in Figure 2.12, it is yet to be developed into a useable and logically laid out toolbox framework which can be applied by the defence technology R & D project team. The draft framework will be finalised once other potential quality tools have been identified and analysed during the survey.

The next chapter will describe the methods adopted to conduct the research, the research design and introduce the main study.

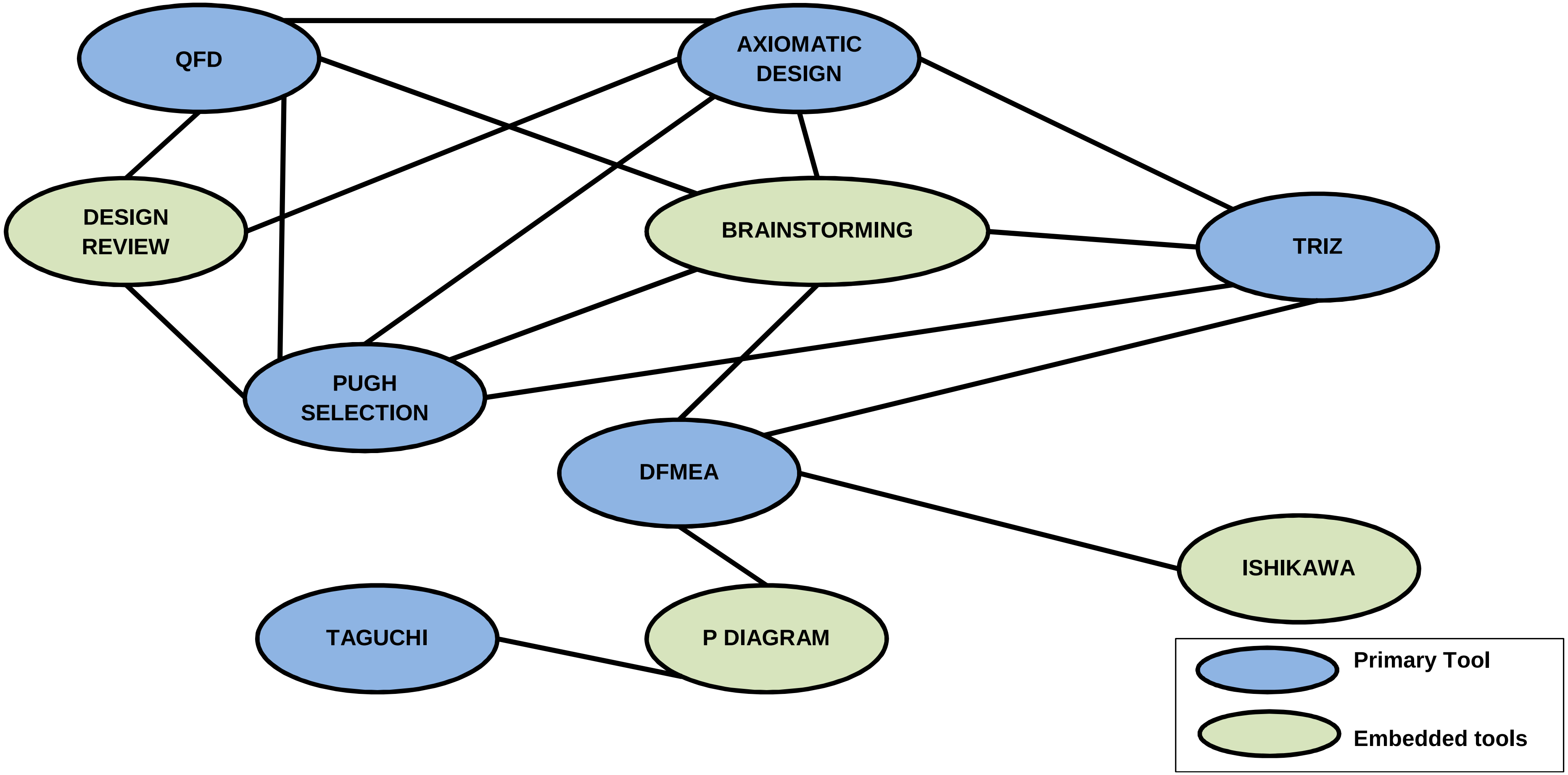


Figure 2.12 Symbiotic Relationships between Quality tools (Source: Researcher's own construction)

CHAPTER 3 RESEARCH DESIGN AND METHODOLOGY

This chapter describes the research design and research methodology adopted in this study, the design of the survey questionnaire, the pilot study, introduces the main study and finally concluding with the perception study. The Chapter further highlights the validity and reliability of the research process and its research instrument.

3.1 Research Design

This section outlines the research process for this study. According to Yin (2009), every type of empirical research encompasses a research design where the design forms a logical sequence that connects the empirical data to a study's initial research questions and ultimately, to its conclusions. Similarly, Leedy and Ormrod (2010) defined research as a systematic process of collecting, analysing and interpreting information with the objective of expanding the researcher’s knowledge on a particular subject that is of importance. The steps undertaken for this research are outlined as follows:

3.1.1 Identify a problem to be researched

Marczyk, DeMatteo and Festinger (2005) broadly defined that the need to conduct research is to find solutions to questions and to gain new knowledge. They added that by conducting research, researchers aim to resolve problems, to identify any connection amongst apparently isolated cases, with the key objective to improve society. Kumar (2011) stated that any question that a researcher wanted to be investigated and any hypothesis that a researcher wanted to challenge or confirm could become a research problem or a research topic for the study. Furthermore, Kothari (2004) stated that research is the search for truth using observations, comparisons and tests, as well as the pursuit of knowledge through logical and objective methods of finding answers to a problem. This research will investigate suitable quality tools to resolve the problems identified in Section 1.2 by means of literature reviews and surveys. The identified quality tools will aim to optimise defence technology R & D project execution by reducing the use of additional resources and project delays and generating high quality technologies for the SANDF.

Kumar (2011) added that the identification of a research problem is the initial and most critical stage of the research process as the research problem provides the basis for a research study, and if it is properly articulated, it is likely that a good study will follow. The statement of the problem for this study is explained in Section 1.2 where it is perceived that problems of project delays and use of unplanned resources arise during redesign activities as a result of quality methods of continuous review of technical requirements, post deliverable quality inspections; design and test cycle process practised during the execution of defence technology R & D projects. This study seeks to investigate these potential inefficiencies with the aim of identifying quality tools to resolves these problems.

3.1.2 Formulate research objectives

Kumar (2011) explained that the objectives of a study are the goals that a researcher sets out to attain. Marczyk et al. (2005) stated that the research objective should be clearly stated as it indicates exactly what the researcher is expected to do in the study. Kumar (2011) agreed that the objectives should be written correctly so that the wording effectively communicates to the readers the intention of the study. The research objectives of this study are stated below, and every attempt was made to achieve the suggestions above when developing these objectives.

- To identify, using a survey, challenges experienced by project teams that are generating redesign activities culminating in project delays and use of unplanned resources during the execution of defence technology R & D projects.
- To identify from a survey, suitable quality tools that are applied during the research (definition) and development (design and testing evaluation) phase to optimise the execution of defence technology R & D projects.
- To develop a framework with tailored quality tools based on literature and survey results which the project team can adopt during the execution of defence technology R & D projects.
- To conduct a perception study of the developed framework with quality tools to determine suitability for defence technology R & D project execution application.

3.1.3 Conduct Literature Review

According to Marczyk et al. (2005), the key function of conducting a literature review is to guide researchers to become acquainted with the work that has already been conducted in the selected area of research. Likewise, Kumar (2011) indicated that one of the primary initial activities in a research study is to review existing literature so that the researcher can get familiar with the existing body of knowledge in the area of study. Hence, the literature of interest selected for this study is in the discipline of Quality tools in R & D projects relevant to the defence technology R & D project execution environment.

Marczyk et al. (2005) asserted that a literature review can be time consuming, intimidating and a demanding process. Kumar (2011) agreed that a literature review can be time consuming, overwhelming and frustrating, but it is an essential aspect of the research study which adds value to almost every step in the research process. Kumar (2011) highlighted that the importance of a literature review is:

a. It provides a theoretical background to the study. The theoretical background of this research is based on quality tools in R & D projects.
b. It helps to establish the links between what the research is proposing to examine and what has already been studied. According to literature in Section 1.2, current quality methods of technical requirement interpretation, inspections, design and test evaluation in defence technology R & D projects are perceived to be inefficient which result in project delays and a waste of resources. The survey undertaken on the R & D project team comprising of R & D Project Managers, SANDF R & D officers, research engineers/scientists and technical support staff will aim identify any links with the quality tools as identified in the literature review to the current practices adopted in the defence technology R & D industry in South Africa.
c. It enables the researcher to show how the findings have contributed to the existing body of knowledge in the researcher’s profession. For this study, key findings identified from the literature review will contribute towards developing a quality toolbox framework related to the defence industry, particularly to R & D technology projects.

Chapter two of this study encompasses a review of various theories on quality tools to optimise defence technology R & D project execution phase that utilises current methods of interpreting SANDF requirements into technical requirements, inspections as well as conducting design and test evaluations to generate quality military technologies.

3.1.4 Collection, Analysis and Interpretation of Data

As reported by Kumar (2011) the key difference between qualitative and quantitative research is that in qualitative research, data is documented in a narrative or descriptive format whereas in quantitative research, data is documented in categorical form or on a scale. Welman, Kruger and Mitchell (2010) listed various methods of collecting data that included standardised tests, survey questionnaires, attitude scales and structured interviews. They stated that a survey questionnaire can be used to collect information on opinions, beliefs and attitudes on any topic or issue. Therefore, this study will make use of a survey questionnaire to obtain views on current challenges and current quality tools within defence technology R & D project execution.

According to Cooper and Schindler (2014), the researcher is responsible for reviewing the assumptions through testing while statistical programs provide diagnostic tools for checking these assumptions. Furthermore, Marczyk et al. (2005) added that to analyse the data, researchers depend on various statistical tools. They mentioned that statistical tools assist the researchers to describe groups and analyse relationships between different variables. Thus, for this study, data analysis would be completed using descriptive statistics such as graphs, median and mode, as well as inferential statistics of hypothesis testing. Kumar (2011) defined a hypothesis as a statement of the researcher's assumptions about the prevalence of a phenomenon or about a relationship between variables that the researcher planned to test within the framework of the study. He emphasised that the hypothesis brings clarity, specificity and focus to a research problem. The hypothesis test of the chi-square test for association will determine whether statistically significant relationships exist between variables of current quality methods and challenges of project delays and the use of unplanned resources.

3.1.5 Conclusion and Recommendations

Welman et al. (2010) mooted that the entire research process must be logically laid out in a report covering all the stages of the research from the formulation of the research problem to the interpretation of the data collected. Hence, this study will culminate with conclusion and recommendations by developing a framework that incorporates useful quality tools which can be used to optimise defence technology R & D project execution in South Africa.

Figure 3.1 shows the process flow of this research study. The next section will explain various research design methodologies, as well as the methodology selected for this study.

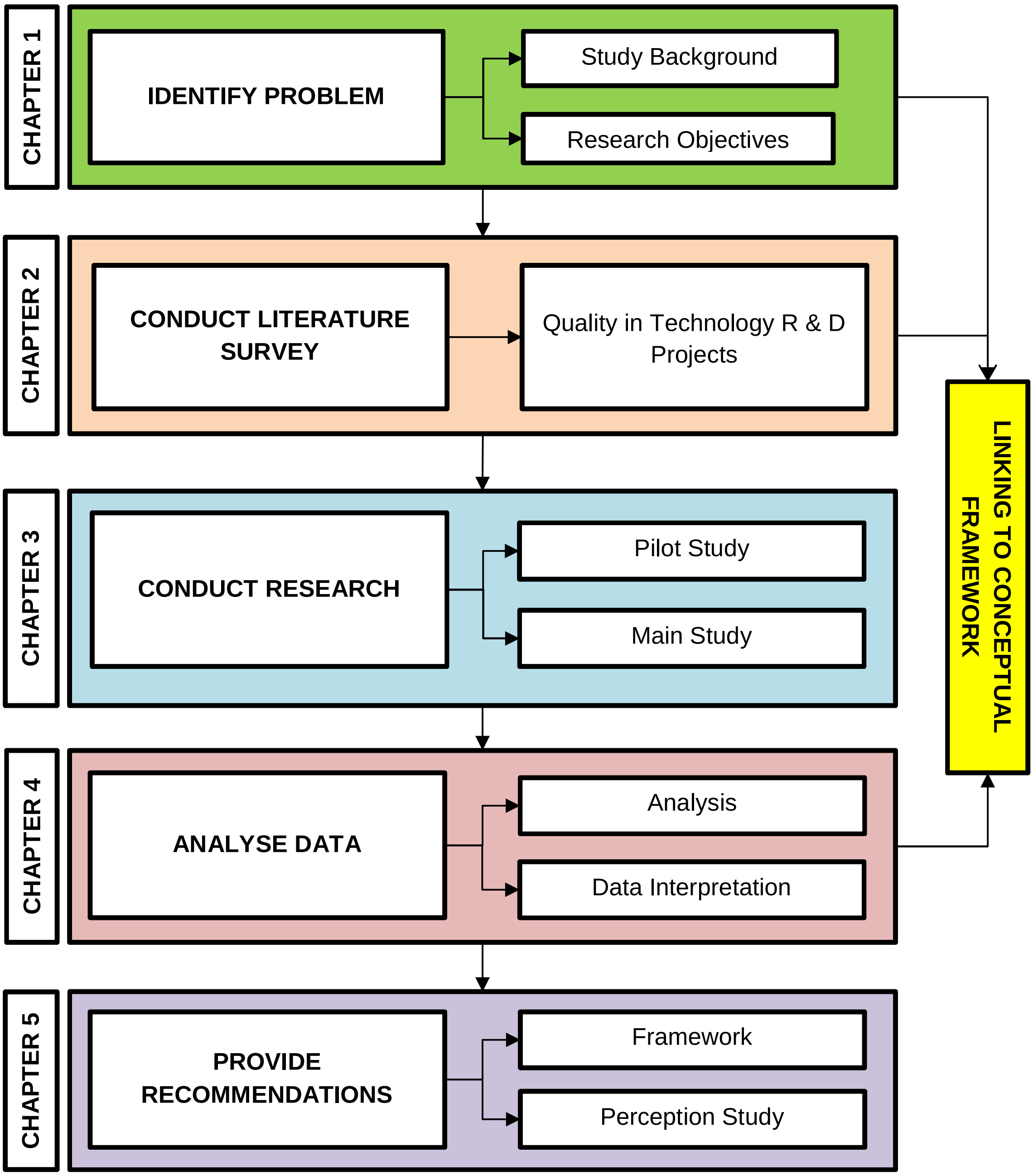


Figure 3.1 Research Flow (Source: Researcher's own construction)

3.2 Research Design Methodology

This section lists several types of case study research, as well as the selection and validity of the research methodology adopted for this study. The section also describes the design and reliability of the survey questionnaire, as well as the method used to analyse data obtained from the survey.

3.2.1 Case Study Methodology

Rowley (2002) acknowledged that case study research frequently emerges as the best choice of methodology for researchers who are pursuing to embark on a modest size research study based on their workplace or the comparison of a limited number of organisations. Likewise, this research is focussed on a workplace project being the State Owned Defence procurement agency which is solely responsible for management and execution of all South African DOD/SANDF funded technology projects in terms of the Armaments Corporation of South Africa Limited Act 51 of 2003 (Armscor, 2014). Hence the outcomes of this research will aim to have an effect on defence technology project execution in the South African defence industry. Rowley (2002) cited Eisenhardt (1989) who stated that case studies are perfectly tailored for new research areas or research areas for which existing theory seems to be lacking. Likewise, the research area of defence technology R & D project execution optimisation through quality tools is a new research area that will be investigated in this study.

Mohd Noor (2008) indicated that a case study is not intended to be undertaken in the entire organisation, but rather it is focussed on a particular matter. Similarly, this research is focussed not on the entire defence industry but is focussed on the technology R & D projects, particularly relating to quality methods used during the execution of these technology R & D projects.

According to Yin (2009), there are single case studies and multiple case studies. Gustafsson (2017) stated that when a study includes more than one case, a multiple case study is required which is often linked to several experiments. Gustafsson (2017) cited Yin (2003) who stated that a single case study emerges as the best choice if a researcher only wants to study one single issue or a single group. Yin (2009) added that a key reason for selecting a single case study method is that a single case study has the ability to confirm, challenge or extend the theory being studied. Furthermore he added that a single case study method can be used to prove whether a theory's propositions are accurate or whether some alternate set of explanations might be more applicable. Likewise, this study will aim to confirm or challenge the existing literature on current problems and quality methods relevant to defence technology R & D project execution environment.

Another reason as reported by Yin (2009) for selecting a single case study is when the case represents an extreme case or a unique case and where a situation exists for the researcher to investigate a phenomenon previously inaccessible to social science inquiry. Similarly, this study may be considered unique or extreme as literature revealed limited or no focus in the area of quality in defence technology project execution. As mentioned previously, it is highly unlikely that there are no quality practices implemented in these industries but rather that the information is confidential, hence the absence of these practices in the public domain. Therefore, there are no existing case studies in this area of quality methods in defence technology R & D project execution that this research could be compared to.

This study will make use of an embedded single case study method. Gustafsson (2017) indicated that a researcher may choose to make a single case study with embedded units. Thomas (2014) illustrated a single embedded case in Figure 3.2 which shows embedded units of analysis. Yin (2009) added that the analysis of these units may be quantitative where embedded case study design call upon surveys or other more quantitative techniques to collect data about the embedded units of analysis. Solomon (2017) referred to Mouton (2014) and Saunders et al. (2003) who stated that the units of analysis could signify the following:

- An individual (Business manager or customer).
- An event (Organisational change, project failure).
- An object (Product, service, process).
- A body of individuals (project team, working group, department, operational unit).
- A relationship (relationship between two or more individuals or bodies, buyer and seller).
- An aggregation (undifferentiated individuals or bodies with no internal structure).

The unit of analysis within the realm of this research is an object which are challenges emanating from the interpretation of SANDF requirements into technical requirements, inspections, as well as design and test evaluations in defence technology R & D project execution. The unit of analysis also encompasses an investigation into quality tools to resolve these challenges. Akwunwa (2013) cited Collis and Hussey (2009) who defined the units of analysis as the variables under investigation to which the research problem refers. Solomon (2017) further defined the unit of analysis as the entity that is being studied during analysis. Figure 3.3 explained the unit of analysis and its variables to be investigated in this study. Yin (2009) advised that sub-units of analysis can provide for extensive analysis and insight into a single case study. The figure illustrates the units of analysis and sub-units (sub-problems) to be investigated in defence technology R & D project execution phase that utilises current quality methods of interpreting SANDF requirements into technical requirements, and inspections as well as conducting design and test evaluations of new generation military technologies. Hence this study will apply an embedded single case study method where data on the unit of analysis will be collected using a survey questionnaire.

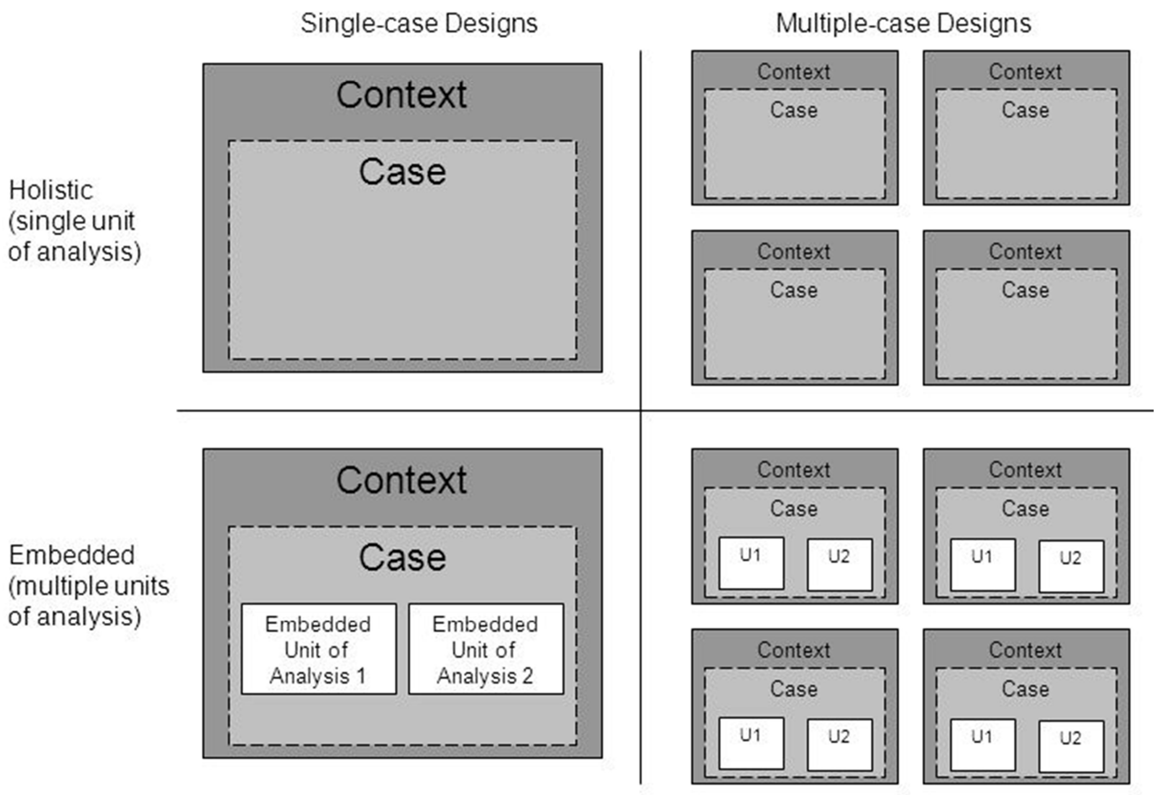


Figure 3.2 Basic types of Designs for Case Studies (Source: Thomas, 2014)

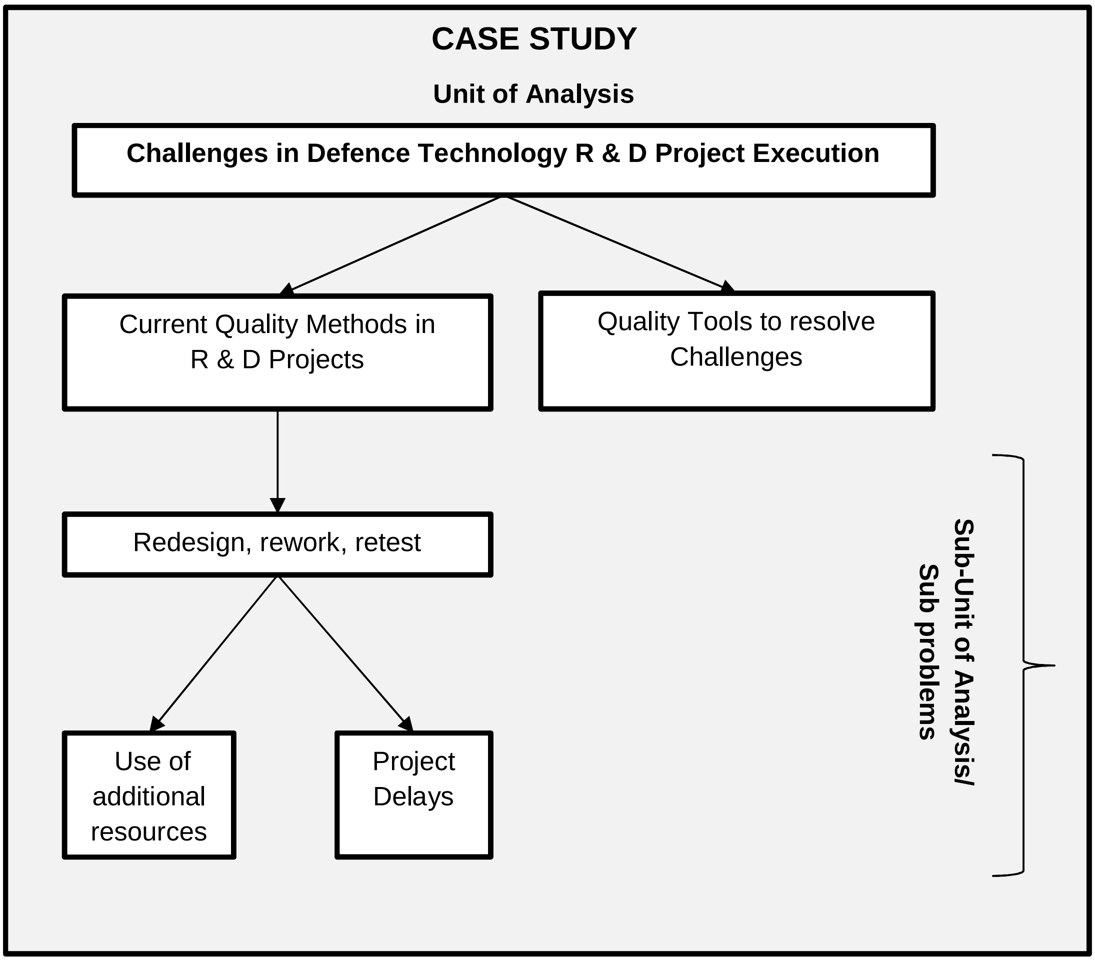


Figure 3.3 Embedded Single Case Study – Units of Analysis (Source: Researcher's own construction)

Moreover, other variables shall also be investigated. Solomon (2017) referred to these variables as the attributes of an individual such as background or gender. Section 1 of the survey questionnaire will collect data on attributes such as position or responsibility of respondents within the defence technology R & D project team.

3.2.2 Validity of the research

Marczyk et al. (2005) defined validity as the measure of a research study's scientific soundness and it is essential for all types of research to generate true and valid results. The following validity methods will be used in this study:

- **Content validity:** According to Cooper and Schindler (2014), content validity of a measuring instrument is the ability to which it offers sufficient coverage of the investigative questions guiding the study. Moreover, Marczyk et al. (2005) highlighted that the measuring instrument must be related to the variables being measured. Therefore, the measuring instrument for this study which is a survey questionnaire will measure the variables as shown in Figure 3.3. The formulation of this measuring instrument originated from the study objectives of this study which is described in Section 3.1.2. Cooper and Schindler (2014) pointed out that determining good content validity involves judgment from the researcher and the process is often intuitive and unique to each researcher.

- **External Validity:** According to Rowley (2002), external validity means establishing the domain to which a study's findings can be generalised. Yin (2009) furthermore stated that results for single case studies can be linked to theory. As this study will make use of a single case study method, the findings that are obtained from the survey will be linked to an established theory or theories identified in the conceptual framework. According to Yin (2009), a single case study can confirm, challenge or extend the theory.

3.2.3 Design of Survey

According to Glasgow (2005), surveys are proficient in gaining information from large samples of the population under investigation. He referred to Bell (1996) who stated that surveys allow for easy generalisation on populations as it can investigate various types and numbers of variables with minimal investment required to develop and administer it. Therefore, due to the ease of studying numerous variables such as the unit of analysis shown in Figure 3.3 which can be linked to the theory on Quality in technology R & D projects and quality problems, a survey method will be used

Welman et al. (2010) stated that a survey questionnaire can be used to collect information on opinions, beliefs and attitudes on any topic or issue. This method will suit this study as the research will endeavour to investigate respondent's attitudes on challenges that are generating redesign activities culminating in project delays and the use of unplanned resources during the execution of defence technology R & D projects. Moreover the survey will investigate quality tools to optimise the execution of defence technology R & D projects

As reported by Kothari (2004), surveys are only concerned with gaining data on existing issues, which implies that surveys are primarily concerned with the present. Thus, he emphasised that variables that exist or have already occurred are selected and observed in surveys. Hence, this study will use surveys to study existing challenges and current use of quality tools in defence technology R & D projects.

3.2.3.1 Survey Media Type

According to Glasgow (2005), verbal surveys may consist of telephone and face-to-face interviews where the face-to-face interview is useful in capturing change in verbal tones, physical gestures and other examples of body language. Glasgow (2005) cited Salant and Dillman (1994) who stated that face-to-face interviews are beneficial where the true population is unknown or where respondents are incapable of responding to written surveys. However, Kumar (2011) mentioned that interviews are time consuming and expensive. On the other hand, Glasgow (2005) stated that written surveys involve minimum resources to administer and are uniquely designed to obtain confidential information. Kumar (2011) further highlighted that a written survey questionnaire provides greater anonymity as there is no face-to-face communication between respondents and researcher and in circumstances where confidential questions are asked, it assists to increase the probability of obtaining accurate information to these confidential questions. Hence, it can be inferred that to save time, cost and to maintain anonymity, the choice of survey medium for this study will be a written survey questionnaire.

Glasgow (2005) confirmed that written surveys are versatile as it can be circulated using either postal or electronic mail and in some instances, can be distributed in person to a group of respondents to evaluate a recent case. Kothari (2004) stated that a mailed questionnaire is the most widely applied method in various research fields. He advised that before administering this method, a pilot study should be conducted to identify any problems with the questionnaire. Therefore, this research will conduct a pilot study to test the questionnaire and thereafter, administer the questionnaire to the respondents using electronic mail.

3.2.3.2 Survey Type Questions

As highlighted by Kumar (2011) the types of questions that are commonly used in social sciences research questionnaires are open-ended and closed-ended type questions. Kumar (2011) suggested that open-ended type survey questions allow respondents to answer in their own words. Glasgow (2005) indicated that open-ended questions are also valuable in obtaining information on a topic with which the researcher is not familiar and thus cannot provide specific response options to the respondents. This is not the case for this study where the researcher is familiar with the field of quality in defence technology R & D project execution. However, Glasgow (2005) cited Salant and Dillman (1994) who noted that open-ended questions involve a deeper understanding and examination to answer on the part of the respondent and, therefore, requires more time to respond. Kumar (2011) also indicated that some respondents may find it difficult to properly word the response to an open-ended question and so information could be misinterpreted. In addition, Glasgow (2005) emphasised that the results obtained from open-ended questions are also more challenging to analyse and it is more demanding to identify a single pattern from the diverse collection of answers which are received from various respondents. Kothari (2004) also agreed that the analysis of open-ended questions is more challenging and as a result, issues with interpretation, comparability and interviewer bias can emerge. Kumar (2011) further confirmed that the analysis of open-ended questions is more demanding as the researcher must carefully perform content analysis in order to correctly categorise the collected information. Marczyk et al. (2005) defined the process of content analysis of transforming qualitative data into quantitative data by means of developing intensive coding procedures. Therefore, due to open-ended questions being more labour intensive in terms of answering, it was not selected as mandatory questions for the respondents. Instead, the use of open-ended questions will serve the function of optional questions where the respondent will also be asked to freely list any challenges and quality tools currently used in defence technology R & D project execution.

In contrast, Kothari (2004) suggested that closed type questions have the benefits of easy handling, simple to answer, are efficient and reasonably affordable to analyse. Glasgow (2005) confirmed that closed-ended type questions are easier for respondents to answer and for researchers to analyse the data. Hence, to save time and make it easier to for the respondents to respond to the survey, closed-ended type questionnaires will be used for this study. Glasgow (2005) cited McIntyre (1999) who stated that closed-ended questions require the respondents to choose from among a given set of responses with ordered choices and require the respondents to examine each possible response independent of the other choices. Kumar (2011) stated that in a closed type question, the likely responses are shown in the questionnaire and the respondent simply marks the response that best explains a respondent’s perception on a particular topic. These choices according to Glasgow

(2005) are based on the type of questions which are provided by Likert scales and numerical scales. The data collection method that will be applied in this study will include a quantitative method where a five-point Likert scale questionnaire will be used to gather data from a sample in the state owned defence technology R & D industry.

The survey questionnaire for this study was divided into 4 sections:

a. Section 1 identified the variable designation group of each respondent from SANDF R & D officers, R & D Project Managers, research engineers and scientists and technical R & D support functions
b. Section 2 was a five-point Likert scale questionnaire of closed-ended questions. This section comprised of 34 questions that will investigate challenges currently experienced during the execution of defence technology R & D projects.
c. Section 3 of the questionnaire required the respondent to choose from a selection of quality methods which are implemented within the defence technology R & D project execution. The quality methods were identified from the literature review on quality methods in technology R & D projects.
d. Section 4 listed two optional open-ended type questions for the respondent to freely provide any supplementary information on challenges experienced during the execution of defence technology R & D projects as well as list any other quality methods being implemented.

Questionnaires will be emailed to the target population. The email will provide details of the research being conducted and that completing the questionnaire will be completely voluntary. All responses will be sent back to the researcher via email.

The questionnaire will be validated using statistics on Microsoft Excel © software. The questionnaire sought to investigate activities that are creating redesign and corrective action activities resulting in challenges of project delays and the use of unplanned resources during the execution of defence technology R & D projects. Furthermore, the questionnaire will investigate the use of quality methods to optimise defence technology R & D project execution.

The next section will explain the design of the questions to obtain the required information from respondents during the survey.

3.2.3.3 Formulation of Survey Questions

As highlighted by Burgess (2001), a crucial part of a good research design is to ensure that the questionnaire addresses the needs of the research and that correct questions are being asked. Burgess (2001) further added that research questions can be formulated through a collective process of reviewing literature and innovative thinking.

Therefore the survey questions to investigate problems that are creating redesign activities culminating in project delays and use of unplanned resources during the execution of defence technology R & D project execution will aim to answer Study Objective 1. The sources of the survey questions are formulated from information obtained during the review of literature and problems called the conceptual framework. Maxwell (2009) indicated that the conceptual framework of a study is often labelled the literature review. However, he stated that what is often called the research problem is also part of the conceptual framework, and the conceptual framework identifies something that is going on in the world including problems. Likewise, the City University of Hong Kong (2014) defined a conceptual framework as comprising of concepts, beliefs, values, problems, assumptions and principles. Thus the conceptual framework of this research study included a literature review of concepts (Chapter 2) and problems identified in Section 1.2. The formulation of survey questions to answer Study Objective 1 on the challenges (problems) is shown in Figure 3.4.

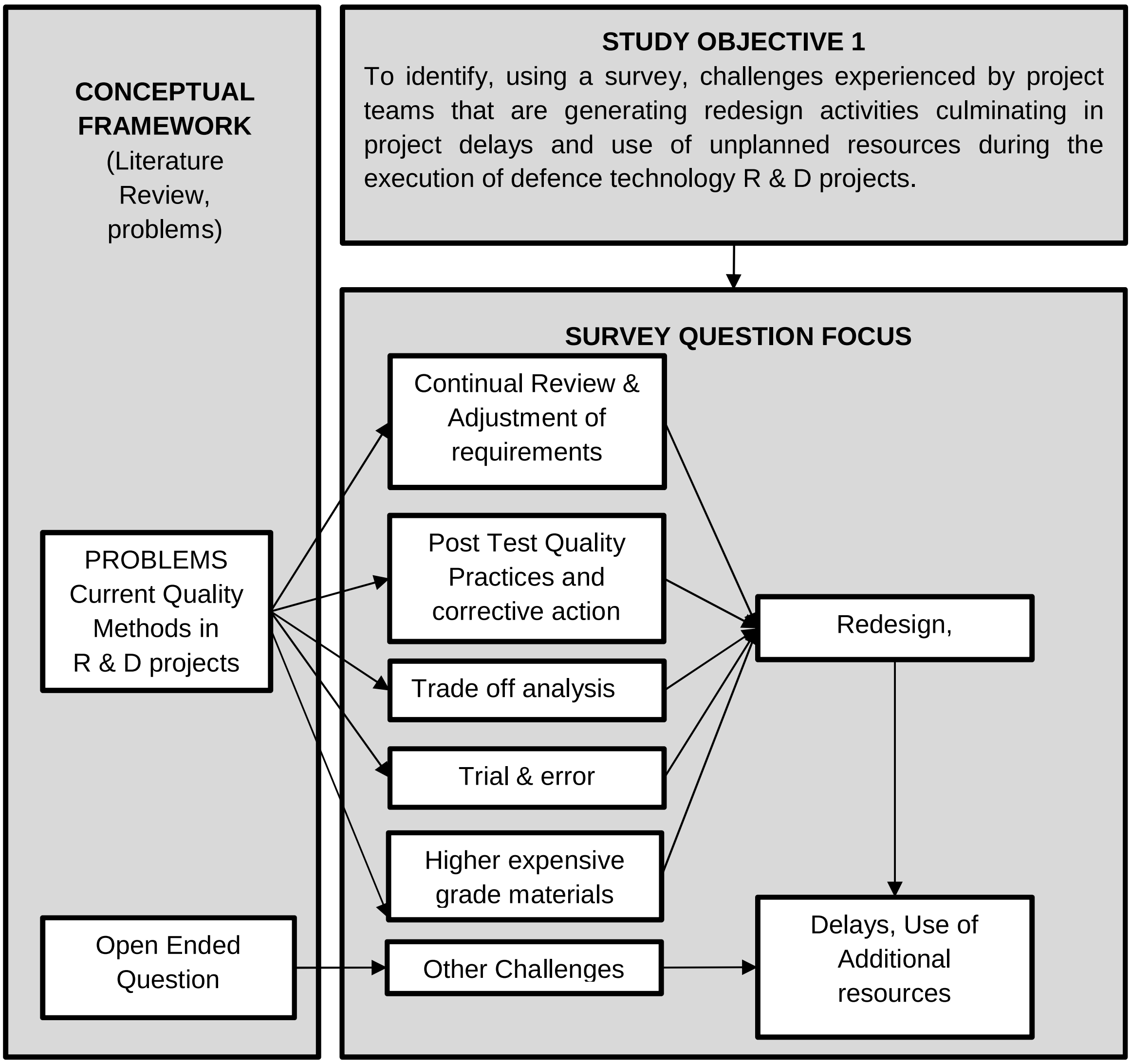


Figure 3.4 Source of Survey questions for Study Objective 1 (Source: Researcher's own construction)

The survey questions to investigate suitable quality tools that are applied to optimise defence technology project execution will aim to answer Study Objective 2. Maxwell (2009) mentioned that the conceptual framework comprises of concepts, assumptions, expectations, beliefs and theories that support and informs the research. The conceptual framework for this study included theory on relevant quality tools in R & D projects that were reviewed in the literature survey. The formulation of survey questions to answer Study Objective 2 on the quality methods is shown in Figure 3.5.

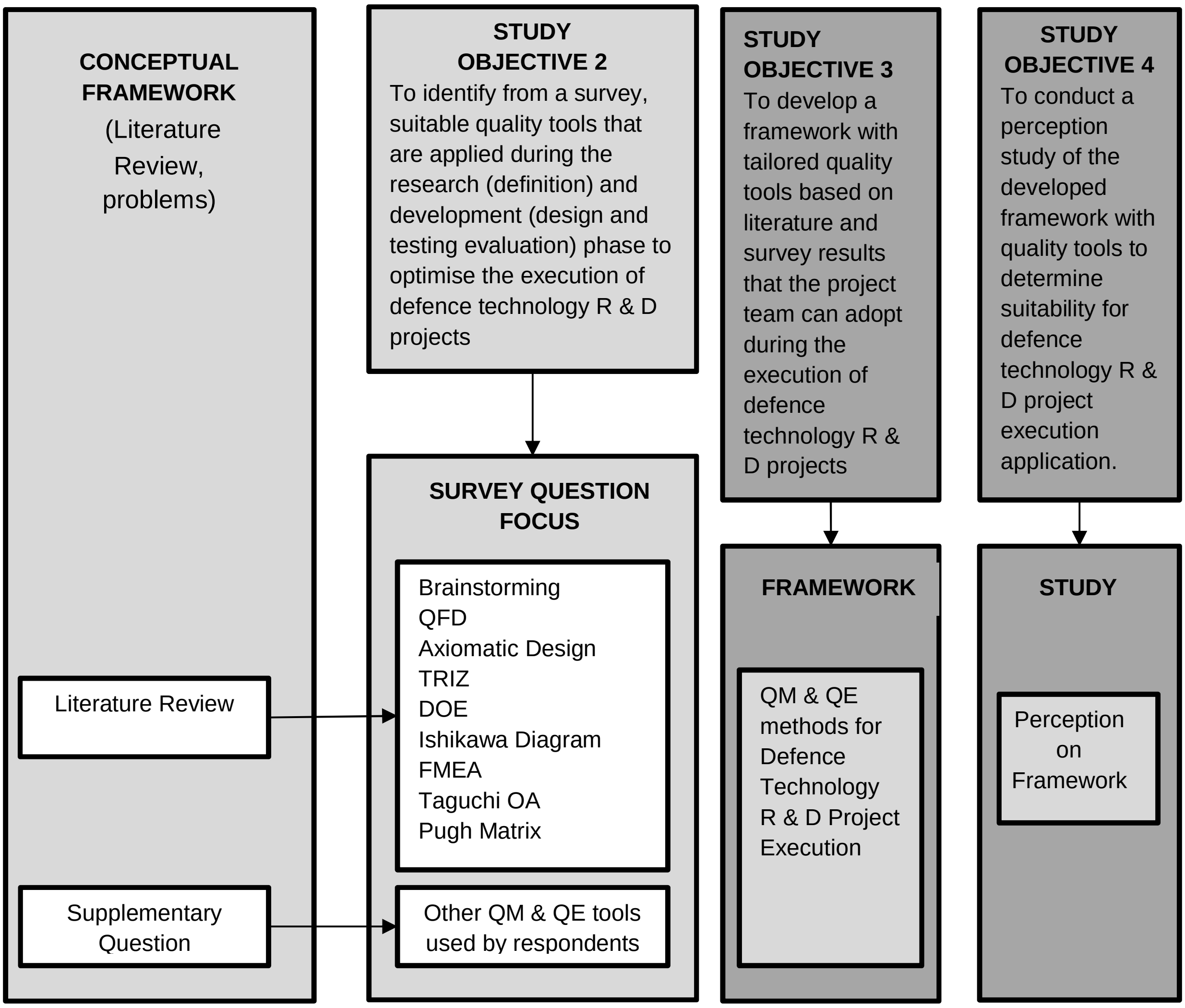


Figure 3.5 Sources of Survey questions for Study Objective 2, 3 & 4 (Source: Researcher's own construction)

Study Objectives 3 and 4 will be answered in Chapters 4 and 5 respectively once the survey has been collected and analysed. It is important to note the relationship between the study objectives. As outlined in the research process stated earlier, the initial step in this process is the identification of problems that are creating redesign activities culminating in project delays and the use of unplanned resources experienced during the execution of defence technology R & D projects. Therefore, Study Objective 1 serves as the catalyst for the continuation of the research to answer Study Objectives 2, 3 and 4.

The survey questions also link back to the unit of analysis identified in Figure 3.3. Rowley (2002) advised that embedded case study designs identify a number of sub-units each of which is explored individually; results from these units are drawn together to yield an overall picture.

3.2.3.4 Reliability of the Survey Questionnaire

Preceding the reliability of the questionnaire is the process of editing the survey data. According to Kothari (2004), editing of data is a method of studying the raw data collected from completed survey questionnaires so as to identify and where possible correct any mistakes. Furthermore, he added that in order to facilitate proper coding and tabulation, editing is practised to ensure that the collected data is precise and reliable with other information collected. The item analysis method is used to identify errors in a questionnaire. Varma (2015) explained that item analysis is a technique of reviewing items in a questionnaire statistically. The University of Wisconsin (2017) stated that item analysis is used to examine whether questions are measuring the fact, idea, or concept for which they were intended. Varma (2015) emphasised that item analysis is conducted after the questionnaire has been administered and data from the real world has been collected. Thus, the questionnaire for this study would be administered to the respondents within the defence technology R & D project execution environment and thereafter item analysis will be conducted on the collected data. Varma (2015) furthermore stated that the objective of item analysis is to identify problematic questions. She defined the following as problematic questions:

- Items may be poorly written creating confusion when responding to them.
- Items may not have a clear and correct response.
- Items may represent a different content area than that measured by the rest of the questionnaire.

Varma (2015) cautioned that a few problematic questions may reduce the overall reliability of the questionnaire. Although the pilot study will also assist in improving the quality of the questionnaire before it is administered to the respondents, the item analysis method provides additional support in improving the quality of the survey data received. Therefore, item analysis will be performed after the main study survey to identify problem questions.

Kothari (2004) described the test of reliability as an important test of sound measurement. A measuring instrument is reliable if it provides consistent results. A five-point Likert scale will be used for Section 2 that will provide consistent measurement in this study. The Likert questionnaire administered in Section 2 of the survey was designed using the PANAS (Positive and Negative Affect Schedule) method. According to Korb (2012), the PANAS measures the Positive Affect and Negative Affect constructs via the Likert scale. Hence, Section 2 of the questionnaire which comprised of mandatory closed ended-questions was split into two equal halves, where one half (Questions 1 to 17) measures positively worded responses and the second half measured (Questions 18 to 34) measured negatively worded responses. Grace-Martin (2008) advised that before an analysis is run on scale items to determine reliability, it is important to reverse code the items that are negatively worded so that a high value indicates the same type of response on every item. Moreover, Kent State University (2018) indicated that reverse coding is a common validation technique for Likert survey items to rephrase a "positive" item in a "negative" way as this can be used to check if respondents are giving consistent answers. Hence, to ensure accurate reliability analysis of the survey questionnaire, the negatively worded group of the questionnaire (Questions 18 - 34) was reverse scored as shown in Table 3.1.

Table 3.1 Reverse Coding of Questions (Source: Researchers's own construction)

Variable Group	Questions	PANAS response	Points per Response	
X	Questions 1 to17	Positive	Strongly Agree Agree Undecided Disagree Strongly Disagree	= 5 = 4 = 3 = 2 = 1
Y	Questions 18 to 34	Negative	Strongly Agree Agree Undecided Disagree Strongly Disagree	= 1 = 2 = 3 = 4 = 5

Korb (2012) explained that the split half reliability method is used to determine how much error in a test score is due to poor test construction. Mishra (2017) admitted that the advantage of using the split half reliability method is that it is less time consuming and minimises environmental, physical and mental fluctuations of the respondent. This implies that if two tests are administered at the same time it will minimise deviations between the two tests and ensure consistency. Once the questionnaire is split into two halves, the next step is to determine the Pearson moment of correlation (See Annexure F). Buley (2000) confirmed that Pearson moment of correlation is a method of determining the strength of these relationships between variables. He added that a researcher uses a measure of relationship to explain how similar two variables are or how much they have in common. For the split half reliability test, Zhang (2010) explained that the questionnaire is divided into two equal halves and the two piles are correlated. Wilson (2009) stated that the correlation is a statistical technique which tells the researcher if two variables are related. He implied that correlation shows to the researcher whether the relationship between the variables is positive or negative, as well as the strength of the relationship. Glen (2018) added that the correlation coefficients are used in statistics to measure how strong a relationship is between two variables and in the case of the Pearson moment of correlation, linear regression is used. Wilson (2009) indicated that a correlation between variables that is greater than 0 is a positive relationship whereas a correlation that is less than 0 means a negative relationship between variables. The correlation between the variables in group X and Y would be clarified using a scatter plot diagram as shown in Figure 3.6. Figure 3.6 indicated that the linear slope (regression) of a scatter plot diagram explains the type of correlation between variables (X and Y) which can be positive, negative or no relationship where r value represents the Pearson moment of correlation. A positive relationship between the positive half of responses (X variables) and negative half of responses(Y variables) will represent a reliable test.

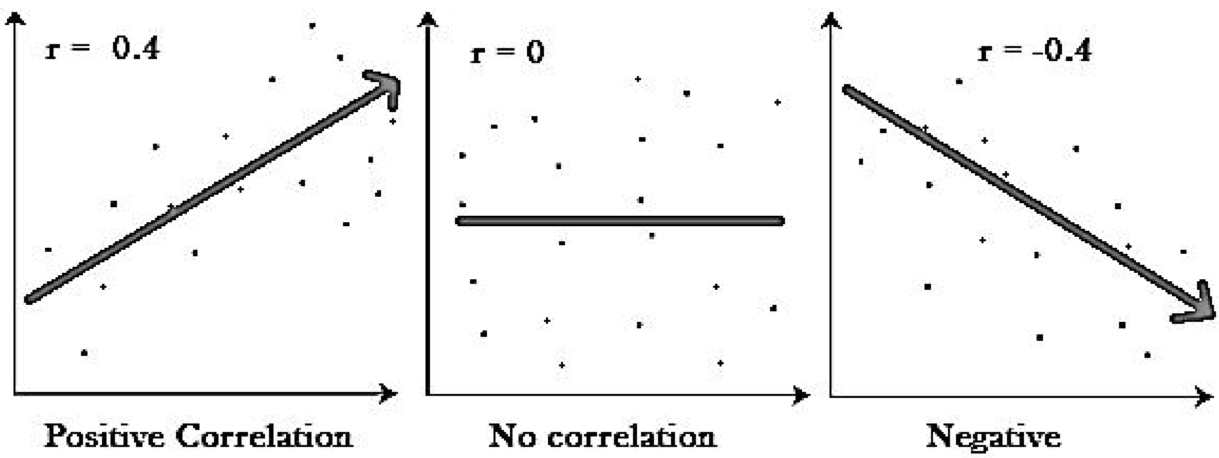


Figure 3.6 Scatter Plot Correlation with Linear Regression (Source: Glen, 2018)

Table 3.2 Relationship strength based on Correlation value

(Source: Glen, 2018)

Correlation Values	**Relationship Strength**
+.070 or higher	Very strong positive relationship
+0.40 to +0.69	Strong positive relationship
+0.30 to +0.39	Moderate positive relationship
+0.20 to +0.29	weak positive relationship
+0.01 to +0.19	No or negligible relationship
0	No relationship [zero order correlation]
-0.01 to -0.19	No or negligible relationship
-0.20 to -0.29	weak negative relationship
-0.30 to -0.39	Moderate negative relationship
-0.40 to -0.69	Strong negative relationship
-0.70 or higher	Very strong negative relationship

After the Pearson correlation coefficient has been calculated to determine the relationship between the X and Y groups, the final step is to validate the reliability of the entire questionnaire by calculating the reliability index. The convenience of split-half reliability method according to Korb (2012) is that two tests are administered once and then reliability index is calculated by coefficient alpha or Kuder-Richardson formula 20 (KR-20) or the Spearman-Brown formula. According to Glen (2014), Cronbach's alpha tests are used to check if multiple question Likert scale surveys are reliable. She explained that Likert scales measure latent variables such as respondent's perceptions on a particular topic which are very challenging to measure in real life. Section 2 of the survey will use a Likert scale to measure the respondent's perceptions on challenges and use of quality methods in Defence Technology R & D projects. Hence, Glen (2014) confirmed that Cronbach's alpha will tell the researcher if the test that was designed accurately measures the variable of interest. The variables of interest that will be measured in this study were derived from the unit of analysis identified in Figure 3.3. Finally, Table 3.3 will be used to interpret Cronbach's alpha value.

Table 3.3 Alpha value interpretations for Likert Scale questions

(Source: Glen, 2014)

Cronbach's alpha	Internal consistency
$\alpha \geq 0.9$	Excellent
$0.9 > \alpha \geq 0.8$	Good
$0.8 > \alpha \geq 0.7$	Acceptable
$0.7 > \alpha \geq 0.6$	Questionable
$0.6 > \alpha \geq 0.5$	Poor
$0.5 > \alpha$	Unacceptable

3.2.4 Analysis of Data

Yin (2009) stated that the analysis of the embedded units in a case study may be quantitative. Yin (2009) confirmed that case studies can include and even be limited to quantitative evidence and embedded case studies use surveys or other more quantitative techniques to collect data about the embedded units of analysis. Therefore, this research will apply this embedded case study design that will use a quantitative survey questionnaire for data collection on the unit of analysis shown in Figure 3.3. Thereafter data would be linked to the study objectives and information grouped as the conceptual framework which is the theory of quality in technology R & D projects, as well as problems identified in Section 1.2. The data will confirm, challenge or extend the conceptual framework.

Kothari (2004) admitted that research studies, in general, acquire large amounts of raw data which must be simplified so that the data can be easily interpreted and analysed. He emphasised that the application of statistical methods is essential in effectively analysing the collected data. Marczyk et al. (2005) added that the data obtained holds a lot of clues to answer the research questions and researchers rely on various statistical methods to unlock the data. The data obtained from the survey questionnaire shall be prepared for analysis using descriptive statistics. According to Nxopo (2011), descriptive statistics is the science of describing a collection of data quantitatively. He mentioned that descriptive statistics differ from inferential statistics, in that descriptive statistics are used to summarise information on an existing set of collected data whereas Kothari (2004) explained that inferential statistics are mainly concerned with hypothesis testing. Cooper and Schindler, (2014) stated that the chi-square test is a widely used inferential statistical method. They added that the chi-square test is used to test for significant relationships between the observed distribution of data among categories and the expected distribution based on the null hypothesis. This study will summarise data on the current situation of challenges, as well as the use of quality tools during defence technology R & D project execution. Therefore, descriptive statistics and inferential statistics will present data on current perceptions. Kothari (2004) listed the important statistical measures that are used to summarise the survey data which are arithmetic average or mean, median and mode.

The data collected on the unit of analysis and variables will be analysed using descriptive statistics such as mode, frequency, correlation, regression, tabulation, graphs and diagrams to present and interpret data. Finally, chi-square test for association will determine whether statistically significant relationships exist between the challenges and the review of technical requirements, Trade Off analysis, Trial and Error, large sample testing, multiple comparative testing and post-deliverable quality inspections methods. Thereafter, data results will be linked to information identified as the conceptual framework. Figure 3.7 summarises the process to analyse the data in this study.

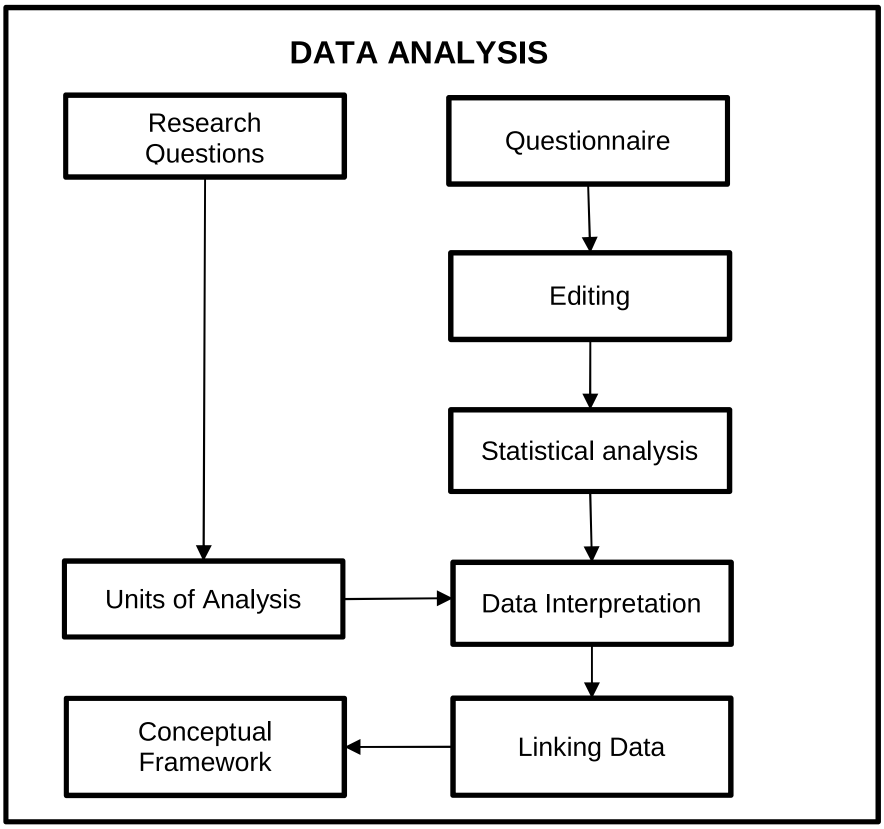


Figure 3.7 Data Analysis Process (Source: Researcher's own construction)

3.3 Pilot Study

This section describes the pilot study process that was conducted to test the survey questionnaire, as well as improve the questionnaire from the responses received.

Welman et al. (2010) stated that a pilot study is specifically valuable if the researcher needs to investigate the validity and reliability of the measuring instrument that has been formulated for the research study. Likewise, Kothari (2004) advised that before commencing with the survey, it is always advisable to conduct a pilot study for testing the questionnaires. Kumar (2011) advised that once the measuring instrument questionnaire has been formulated, it is imperative that the questionnaire is tested before using it for actual data collection. Kothari (2004) explained that a pilot study survey is the replica and rehearsal of the main study survey. Such a study Kothari (2004) added brings to light the weaknesses of the questionnaires, as well as the survey techniques and from the feedback, improvement can be affected. As explained by Kumar (2011), pre-testing the measuring instrument requires a critical evaluation of each question and its importance as interpreted by a respondent and a pre-test should be undertaken in the actual operational environment on a group of people similar to the study population. Therefore, during the pilot study, the survey questionnaire of this study was administered through the same medium as the main study being the electronic format of email.

Once it had been identified that a pilot study to test the questionnaire is valuable, the next step was to determine the sampling method and size for the pilot study.

3.3.1 Sample method and size

Marczyk et al. (2005) explained the sample of convenience is simply a potential source of respondents that is easily accessible to the researcher and in many instances; the study might simply focus on randomly selecting respondents from one facility. Leedy and Ormrod (2010) stated that convenience sampling takes people who are readily available. Kothari (2004) added that when respondents are chosen to be included in the sample based on the ease of access, it can be referred to as convenience sampling. He further explained convenience sampling is an unrestricted non-probability sampling method where respondents for the sample are selected purposely by the researcher. The sampling method that was adopted for the pilot study in this study was convenience sampling where respondents were randomly selected from individuals in close proximity and ease of access to the researcher.

Therefore, a pilot study comprising of a questionnaire will be conducted with a small group of subjects from the South African defence technology R & D project execution environment. Feedback from the pilot study will provide input in further developing and refining the survey questionnaire.

3.3.2 Pilot Study Process

The survey questionnaire was designed as stated in paragraph 3.2.3 and tested during a pilot study. The questionnaire was administered to five respondents who were sampled through the non-probability convenience sampling method. The questionnaire was emailed to the respondents. This will also be the preferred method of administrating the questionnaire during the survey of the main study.

The pilot survey package that was emailed to the five respondents included the following sections:

- Letter of information regarding the aim of the study
- Consent form to grant permission to publish results

- Survey questionnaire to be tested
- Feedback form on questionnaire quality

The feedback form required criticism on the design of the questionnaire. The following closed-ended questions were included in the pilot survey:

- Instructions to answer questionnaire were clear.
- Survey questions were understandable and unambiguous.
- Estimated time to complete the survey.
- The questions were effective in identifying relevant inefficiencies in defence technology R & D project execution.
- The questions were effective in identifying relevant quality methods to optimise technology concepts in defence technology R & D project execution.

In addition, the respondents were given the opportunity to provide their own recommendation as to how to improve the questionnaire with the following open-ended question.

- Were there any other aspects of the survey questionnaire that requires improvement? If so, please advise?

3.3.3 Results of Pilot Study

Kumar (2011) emphasised that the aim of the pilot study is not to collect data but to recognise issues that the respondents could have in either understanding or interpreting a question. Therefore, he stated the objective is to investigate if there are issues in understanding the way a question was formulated, it relevance and whether different respondents interpret the same question differently.

The following feedback on the questionnaire was unanimous:

- The instructions to answer questionnaire were clear
- All respondents were able to complete the questionnaire in approximately 30 minutes.

The following recommendations were made by the respondents:

a. Survey questions in section 2 were not detailed enough and could create ambiguity amongst respondents. Hence questions in Section 2 were enhanced and provided more clarity as possible in areas where challenges were perceived to occur.
b. The selection of quality methods in Section 3 to optimise inefficient methods in the execution of defence technology R & D projects may not be familiar to many respondents and hence it would be difficult for them to select those methods from the option list provided. Therefore, for convenience, a list of definitions that explained the function of each quality tool listed in Question 35 was also attached to the questionnaire. Furthermore, the questionnaire does provide for an optional open-ended question that asked the respondent to list their own quality methods as well.

Based on the recommendations, the questionnaire was revised and henceforth the questionnaire was ready to be implemented in the main study.

3.4 Main Study

This section explained the process that was applied to conduct the main study which included:

- Identifying the target population
- Selecting sample size and sampling method
- Process of administering the main study

3.4.1 Target Population

According to Welman et al. (2010), a population refers to the study object and can consist of various groups, companies and humans. Therefore, the population for this study was state owned defence technology R & D project environment in South Africa.

3.4.2 Sampling Method and Sample size

A non-probability purposive sampling method will be used. According to Welman et al. (2010), non-probability samples are less complicated and economical in both time and expenses. Leedy and Ormrod (2010) added that in non-probability purposive sampling, people are chosen for a specific purpose and from a specific group. Hence for this study, individuals will, therefore, be selected from SANDF research and development staff officers, research and development project managers, research scientists, engineers and research support functions that make up the R & D project team that executes defence technology R & D projects.

Welman et al. (2010) acknowledged that non-probability purposive sampling technique works very well with small or special samples. Moreover, studies have revealed an alarming trend in low survey responses which result in small samples being received. Rindfuss, Choe, Tsuya, Bumpass and Tamaki (2015) cite Atrostic et al. (2001), de Leeuw and de Heer (2002), Groves (2011), Bethlehem et al. (2011) and Brick and Williams (2013) who all reported a steady decline in survey respondent cooperation particularly in surveys conducted in government sectors. The US National Research Council (2013) also revealed a decrease in survey participation over time across a number of social science disciplines in America and abroad. Rindfuss et al. (2015) cited Dillman et al. (2009) who reasoned that responding to surveys has changed from being an obligation to being a matter of the respondent's choice and convenience. Likewise, due to this global phenomenon, a low response rate could be anticipated during this study's survey as it is voluntary and no obligation is required from the respondent to complete the questionnaire. Furthermore, a review of previous research studies that employed survey questionnaires also revealed a low survey response rate. For example, Zhang (2010) received a modest sample size of 35 respondents from small enterprises to explore Quality Management within small businesses in South Africa. Likewise, Zinzi (2011) who examined Quality Management in manufacturing companies in the Western Cape, South Africa, received a small sample size of 30. Finally, Investigating Quality Improvement at a tertiary institution, Akwunwa (2013) analysed a response of 44 from a target population of 500.

Hence, due to low survey response rates experienced by numerous previous studies locally and abroad, the question remains, what is regarded to be an acceptable response rate? Doherty-Bigara (2014) noted that it is difficult to determine what the precise sample size should be in order to obtain both a high level of accuracy, in terms of sufficient diversity of viewpoints and sufficient redundancy of answers. He reasoned that if the sample size is too large, then there is too much redundancy and if the sample size is too small, then an insufficient number of diverse responses will be received and inaccuracy ensues. Hence, it is important that an acceptable sample size is determined for the study so as to have a balanced perspective in terms of diverse views and redundancy of similar responses. Doherty-Bigara (2014) who cited Cooper and Schindler (2001) stated that producing a sample size that exceeds 5% does not affect precision. Furthermore, he concluded that a sample size of between 5% and 15% of the total population will provide a good representation of answers in terms of sufficient diversity and sufficient redundancy. The questionnaire was administered to at least 250 respondents. Hence due to low survey response rate trends, this study will aim to get a response rate within the acceptable range of between 5% and 15%.

3.4.3 Main Study Process

The survey questionnaire was designed as stated in paragraph 3.2.3 and tested during the pilot study in Section 3.3. The questionnaire was submitted to at least 250 respondents that were sampled through non-probability purposive sampling method.

Questionnaires were mailed to the respondents with a request to return them after completing them. According to Kothari (2004), the advantages of mailing a questionnaire are as follows:

- It is affordable even when the population is large and is widely spread geographically.
- Respondents have sufficient time to provide properly thought out answers.
- Respondents, who are not easily accessible, can also be contacted conveniently.
- It can be issued to large samples and hence the results can be more dependable and reliable.

However, Kothari (2004) also listed the disadvantages of a mailed questionnaire as follows:

- Low response rate of completed questionnaires.
- There is no flexibility in that once the questionnaire has been administered; there is no opportunity to update the questionnaire.
- There is also the possibility of vague responses or uncompleted questionnaires being received.

- It is difficult to ascertain as to whether willing respondents are truly representative.

As stated by Burgess (2001), where the questionnaire is administered by post or electronic mail, it is common practice to attach a letter of information that details what the questionnaire is about and why its completion is necessary. Therefore, the following documents were submitted to the potential respondents:

- Letter of information providing background and aim of the study,
- Letter of Consent,
- Instructions to complete questionnaire, and
- Questionnaire consisting of section 1, section 2, section 3 and section 4.

During the mailing of the questionnaires anonymity and confidentiality was upheld. According to Welman et al. (2010), anonymity is important as it will allow the respondents to freely express their true opinions. The Blind Carbon Copy (BCC) function of emailing allows contacts of respondents to be concealed. Marczyk et al. (2005) state that confidentiality involves both an individual's right to have control and access over his or her personal information, as well as to have that information kept private. All responses will be collated by the researcher and securely stored for a period of 5 years on a password protected PC. The researcher has the necessary security classification to handle confidential information.

Based on the results and analysis of the main study, a framework with suitable quality tools to optimise defence technology R & D project execution will be developed and its effectiveness will be evaluated using a perception study.

3.5 Perception Study on the Quality Toolbox Framework developed during this study

This section describes the process of the perception study to evaluate the developed framework with quality tools to determine suitability for defence technology R & D project execution application.

According to Erickson (2013), perception studies use surveys to assess needs, solve problems and analyse trends. She claimed that one of the main reasons why companies conduct perception surveys is to obtain information on future trends, identify gaps and provide recommendations. Similarly, the perception study aimed to identify gaps, obtain recommendations to improve the framework for future use in the defence technology R & D project execution environment. The following aspects will be investigated on the framework during the perception study:

- **Design of Framework**
  - Ø Layout,
  - Ø Instructions to use the framework.
- **Content in Framework**
  - Ø Comparison with other similar frameworks,
  - Ø Need for training on methods, and
  - Ø Effectiveness of methods in reducing project delays and use of additional resources.

As was the case for the pilot study, the sampling method that will be adopted for the perception study will be convenience non-probability sampling where respondents with the appropriate knowledge will be randomly selected from individuals in close proximity and ease of access to the researcher. The questionnaire will be submitted to at least 10 respondents through convenience non-probability sampling method. As was the case with the main study, the following documents will be submitted to the potential respondents:

- Letter of information providing background and aim of the perception study,
- Letter of Consent,
- Questionnaire with instructions, and
- Quality Toolbox framework program on Microsoft© Excel.

3.6 Summary of the chapter

The chapter provided an overview of the single case study research design process that was selected for this study. Content and external validity relevant to this study was discussed. The formulation of the questionnaire based on the study objectives of this study to investigate challenges, as well as suitable quality tools to solve these challenges were presented. Item analyses, split half, regression and Pearson correlation methods to check reliability of the questionnaire were revealed. Analysis of the collected data using descriptive statistics such as mode, frequency, tabulation, graphs and diagrams, as well as chi-square inferential statistics were explained. The pilot study, the main study and perception study processes were shown. Feedback from the pilot study was used to optimise the questionnaire for the main study. Finally, the perception study process to evaluate the developed framework with quality tools to optimise defence technology R & D project execution was discussed.

Chapter 4 will provide the results and analysis of the main study.

CHAPTER 4 RESULTS AND ANALYSIS

An objective of this study was to identify, using a survey, the challenges experienced and the quality methods used currently within defence technology R & D project execution. This chapter thus presents the results and discusses the findings of the above. The presentation of the results begins with an analysis of the reliability of the questionnaire using item analysis, as well as split half reliability. The survey questionnaire is split into four sections where each section is analysed, and its results are presented in the form of descriptive statistics (median, mode), inferential statistics (hypothesis testing using chi-square analysis), graphs and tables using Microsoft Excel©. Thereafter, the data collected from the responses are compared with the findings in the literature.

The conclusions drawn by the researcher was obtained from the statistical data. The statistical data was validated, assessed and verified as being correct by the University statistician (Annexure H).

4.1 Survey Reliability Testing

This section presents the reliability of compulsory Section 2 of the questionnaire through item analysis and split half reliability testing. Section 2 was divided into 4 subsections which formed the bulk of the questionnaire and posed mandatory questions relating to the challenges and quality methods in defence technology R & D project execution as identified in literature. The number of responses received from the South African defence technology R & D project environment was eventually 40 even with an extreme effort of reminders sent by the researcher. However, the sample size was within the acceptable range of between 5% and 15% of the target population (Doherty-Bigara, 2014). Nevertheless, it should be emphasised that low survey responses are a common phenomenon in research studies as revealed in Section 3.4.2. Pryor (2017) pointed out that there is an assumption that the higher the response rate is to the survey, the more accurate the results will be because traditionally, people relate a low response rate with inaccurate results. Contrary to this belief, Fosnacht, Sarraf, Howe and Peck (2013) proved during a study that low response rates can provide reliable survey results. Using over 500 students from over 300 tertiary institutions, they discovered results to be reliable under low response rate conditions ranging from 5 to 25 percent and as few as 25 to 75 respondents. This study revealed that additional effort spent by the researcher to obtain higher response rates will at most times not significantly alter the results of the survey. Thus, Pryor (2017) advised that a researcher's valuable time should be better spent on improving the survey instrument and analysing the data rather than attempting to obtain higher response rates. Likewise, further findings from Fosnacht et al. (2013) study suggested that researchers should pay more attention to minimising sources of potential error when evaluating data quality rather than focusing on non-responses. Moreover, Peytchev (2013) was concerned that overwhelming attention given to the response rate might distract the researcher's attention from other important issues during the survey such as measurement and sampling error. Therefore, based on the evidence that supports the view that reliable results can be obtained from modest response rates, the reliability of this survey is discussed in the following sections.

4.1.1 Item Analysis of Section 2 Questionnaire

Varma (2015) cautioned that a few problematic questions may reduce the overall reliability of the questionnaire. Hence, it is important to identify these problem questions before analysing the data. Item analysis was determined by calculating the correlation between the respective item and the total sum score (without the respective item) referred to as the item-total correlation value. Varma (2015) indicated values below 0.15 are shown to be problematic. Table 4.1 shows the item-total correlation values for the respective questions for Section 2. Section 2 of the questionnaire consisted of mandatory questions and is the most significant component of the survey questionnaire. Korb (2012) advised that when multiple constructs are being assessed, the researcher should separate the questionnaire into different parts or constructs and calculate the reliability separately for each construct of interest. Therefore, the questions were grouped into four subsections or constructs of interest as shown in Table 4.1 that investigated variables linked to the unit of analysis of this study as illustrated in Figure 3.3. Reliability of each subsection was calculated by taking measurements of questions investigating the same issue. The Cronbach values for the subsections showed good reliability except for the subsection on perception of quality methods and redesign challenges which revealed a questionable alpha value of 0.6394, as well as a questionable alpha value of 0.6833 respectively. However, by removing all problem items with item-total correlation values of less than 0.15, the Cronbach value for the subsection on redesign challenges improves to 0.7230, whereas the Cronbach value for perception of quality methods increased to 0.7530. Hence, Section 2 comprising of questions 1 to 34 proved to be internally consistent.

Table 4.1 Item Analysis of Section 2 (Source: Researcher's own construction)

NO.	Question	Item-Total Correlation	Cronbach Alpha if item deleted
Project Delays and use of Unplanned resources challenges			
Q1	Question 1	0.6317	0.6540
Q2	Question 2	0.6601	0.6834
Q18	Question 18	0.4477	0.7165
Q19	Question 19	0.5241	0.6992
	Cronbach Alpha for items		**0.7620**
Technical Requirement Challenges			
Q4	Question 4	0.5572	0.7036
Q5	Question 5	0.5135	0.6856
Q21	Question 21	0.5242	0.8237
Q22	Question 22	0.5639	0.6856
	Cronbach Alpha for items		**0.7800**
Perception on Quality methods			
Q3	Question 3	0.5074	0.5951
Q6	Question 6	0.4493	0.6027
Q7	Question 7	0.2523	0.6044
Q8	Question 8	0.4757	0.5915
Q9	Question 9	0.5214	0.5991
Q10	Question 10	-0.0925	0.6520
Q11	Question 11	0.4033	0.6234
Q16	Question 16	0.1218	0.6463
Q17	Question 17	0.2155	0.6518
Q20	Question 20	0.2270	0.6220
Q23	Question 23	0.2668	0.6063
Q24	Question 24	0.5303	0.5960
Q25	Question 25	-0.0252	0.6460
Q26	Question 26	0.2595	0.6168
Q27	Question 27	0.1313	0.6419
Q28	Question 28	0.3939	0.6228
Q33	Question 33	-0.1215	0.6443
Q34	Question 24	-0.2459	0.6823
	Cronbach Alpha for all items		**0.6395**
	Cronbach Alpha with problem items deleted		**0.7530**
Redesign Challenges			
Q12	Question 11	0.6612	0.6119
Q13	Question 13	0.4021	0.7111
Q14	Question 14	0.5119	0.6034
Q15	Question 15	0.3791	0.6442
Q29	Question 29	0.4128	0.6364
Q30	Question 30	-0.0840	0.7230
Q31	Question 31	0.4893	0.6511
Q32	Question 32	0.2631	0.6277
	Cronbach Alpha for all items		**0.6833**
	Cronbach Alpha with problem items deleted		**0.7230**

4.1.2 Split Half Reliability (Pearson Moment of Correlation) of Section 2

Using Microsoft© Excel, the Pearson moment of correlation between variables of the positive half (Questions 1 to 17) and the negative half (Questions 18 to 34) for the survey was calculated to be +0.5170. Using Table 3.2 to interpret this value, a strong positive relationship existed between the responses of both halves. However, this correlation included the problematic items identified during the item analysis in Section 4.1.1. Deleting these ambiguous items increased the correlation significantly to +0.6146. Referring to Table 3.2, this value is also interpreted as a strong positive relationship between both halves of the questionnaire. Varma (2015) advised that ambiguous questions should be omitted as it will yield inaccurate data and thus reduce the overall reliability of the questionnaire.

Furthermore, correlation between the variables is further clarified using a scatter plot diagram. Figure 4.1 indicates the distribution of the responses between both halves of the questionnaire using a scatter plot diagram. The linear regression of the distribution is illustrated using an arrow. Using Figure 3.6 as a reference, the direction of the arrow implied that the correlation between both halves is positive.

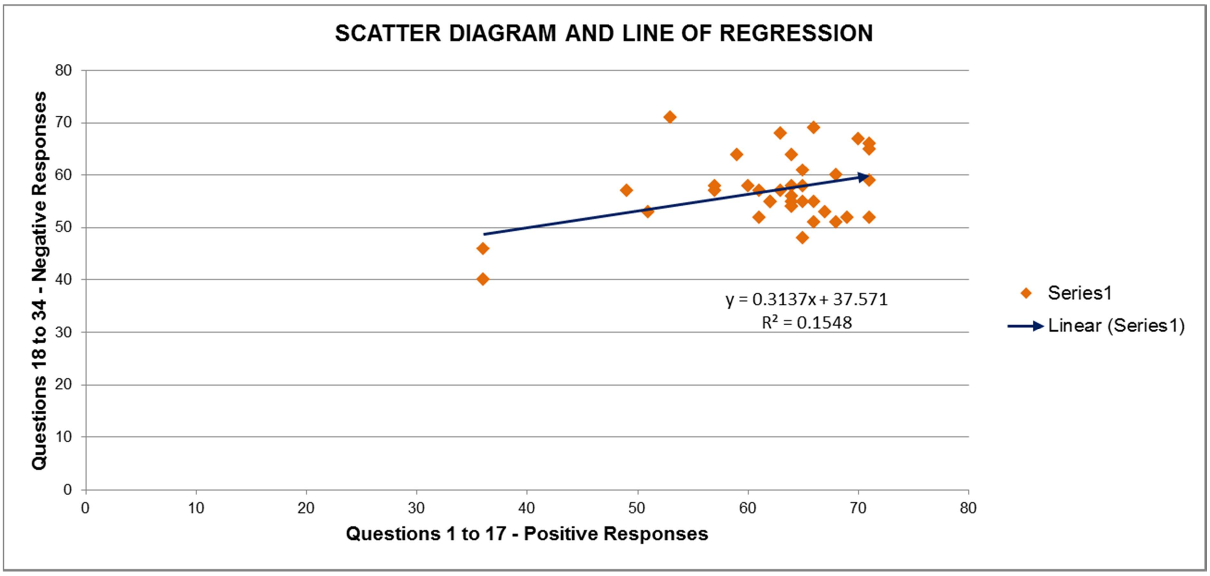


Figure 4.1 Scatter Plot diagram and linear regression with items deleted (Source: Researcher's own construction)

Questions 1 to 34 (Section 2) of the survey questionnaire was the largest section. This section was the most important part of the questionnaire as it required the respondents to answer all the questions in the section. Problematic questions were identified using item analysis and removing these items improved the internal consistency and split half reliability of the section. Based on these results, Section 2 proved to be reliable and an analysis of the responses is explained in Section 4.4.

4.2 Results and Analysis of Section 1

This section describes the demographics of the respondents in terms of their functions within the defence technology R & D project execution. The technology R & D project team comprises of R & D project managers, SANDF R & D officers, research scientists or engineers and technical support staff such as quality representatives, administrators, artisans and technicians.

Figure 4.2 indicates the representation of respondents for the survey:

- Majority of respondents represented were R & D project managers (49%).
- Research engineers/scientists and technical support function were satisfactorily represented (22% and 30%).
- The remaining respondents were SANDF R & D officers (8%).

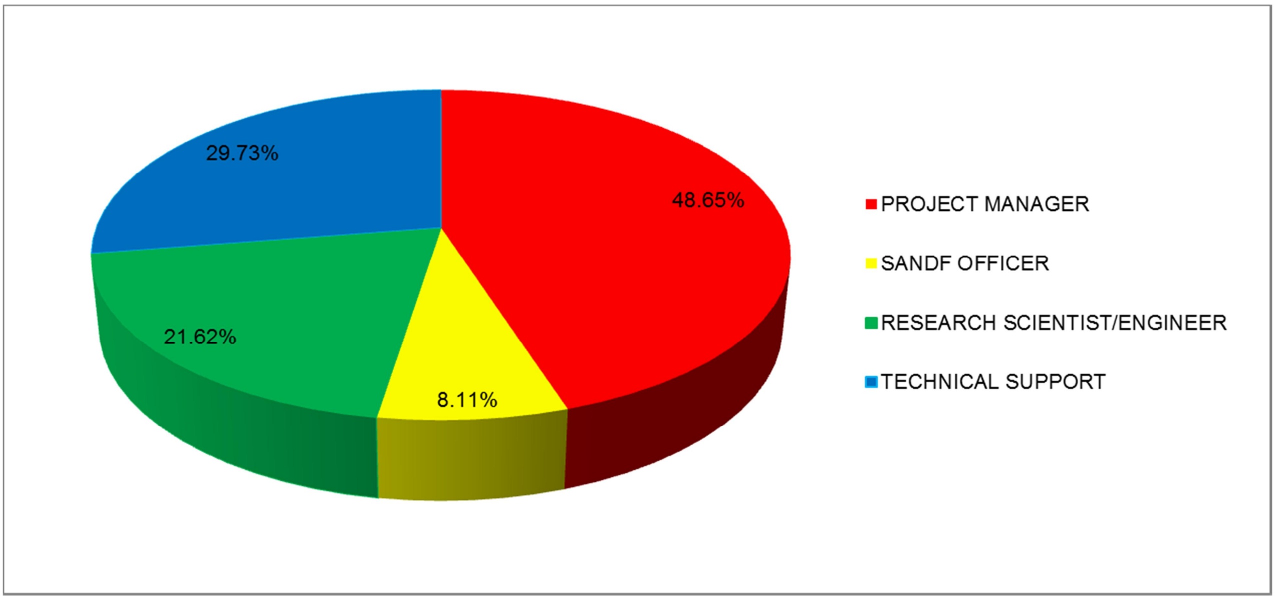


Figure 4.2 Designation of respondents (Source: Researcher's own construction)

Wingate (2015) acknowledged that R & D project managers are experienced and knowledgeable leaders who are responsible for successfully implementing a technology R & D project. As a result, it was assumed that R & D project managers have the broadest knowledge of challenges and use of quality tools within defence technology R & D project execution. Furthermore any new knowledge acquired to optimise defence technology R & D project execution may require the leadership of the R & D project manager to successfully implement these new methods. Therefore, defence technology R & D project managers were considered important contributors of data for this study.

4.3 Results and Analysis

This section revealed the results obtained from the questions in Section 2, 3 and 4 that examined challenges and the use of quality tools within defence technology R & D project execution. Microsoft© Excel was used to analyse the data. The results were presented as univariate graphs, tables and figures.

4.3.1 Results of Mandatory Closed-Ended Questions 1 to 34 (Section 2)

This section explains the results of Section 2 which comprised of 34 mandatory questions. The questions were subdivided into 4 groups that investigated variables linked to the unit of analysis of this study. The variables were grouped into the following categories:

- Project Delay and Use of Unplanned Resources Challenges,
- Technical requirements Challenges,
- Perception of Quality Methods currently used, and
- Redesign Challenges.

4.3.1.1 Project Delay and Use of Unplanned Resources Challenges

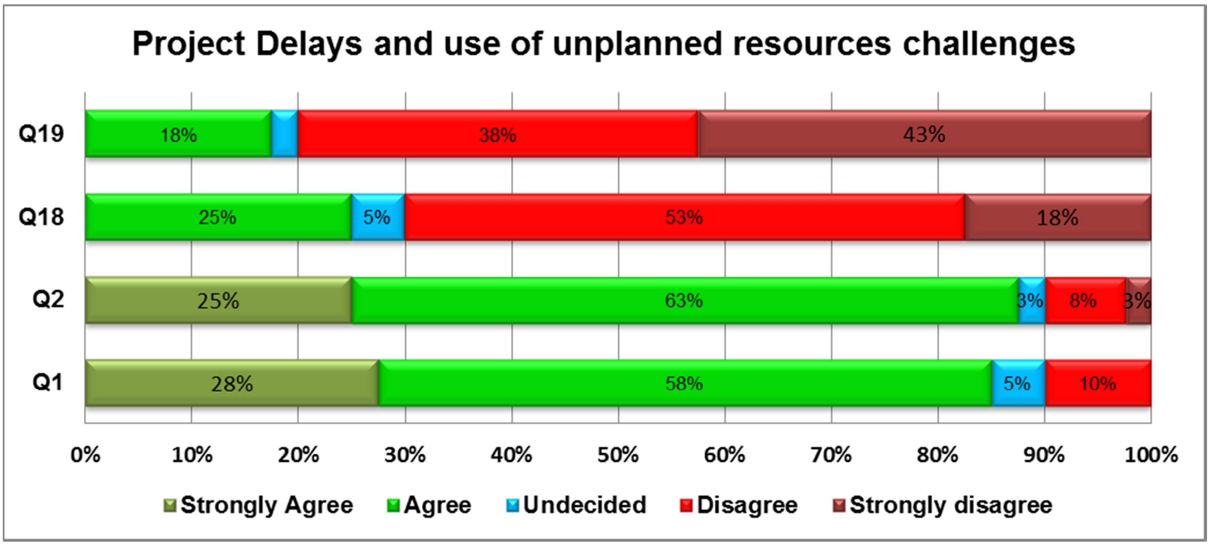
It is acknowledged that Defence technology R & D projects are technically high risk in nature and a high level of uncertainty is expected in its activities. Hence, it is expected that technology R & D project teams make use of unplanned resources and tend to extend deadlines during the execution of defence technology R & D projects to complete the required technology concept. Nevertheless, it can be perceived from literature that in today's environment of reduced defence budget, defence organisations can no longer afford the use of unplanned cost and extended timescales that technology R & D projects have experienced thus far. The following questions aimed to clarify that R & D project teams do concede that the use of unplanned resources and project delays do occur in defence technology R & D project execution.

According to Figure 4.3 the respondents agreed to the following:

- Question 1: Additional unplanned resources are required in Defence technology R & D project execution (86% Agreed to Strongly Agreed).
- Question 2: Project deadlines have to be extended in Defence technology R & D project execution (88% Agreed to Strongly Agreed).

According to Figure 4.3 respondents disagreed to the following,

- Question 18: All resources to be used in Defence technology R & D project execution can be determined before commencement (71% Disagreed to Strongly Disagreed).
- Question 19: Defence technology R & D projects can be successfully completed within the planned project deadline (81% Disagreed to Strongly Disagreed).



Question	Median	Mode	Question	Median	Mode
Q1	Agree	Agree	Q18	Disagree	Disagree
Q2	Agree	Agree	Q19	Disagree	Strongly Disagree

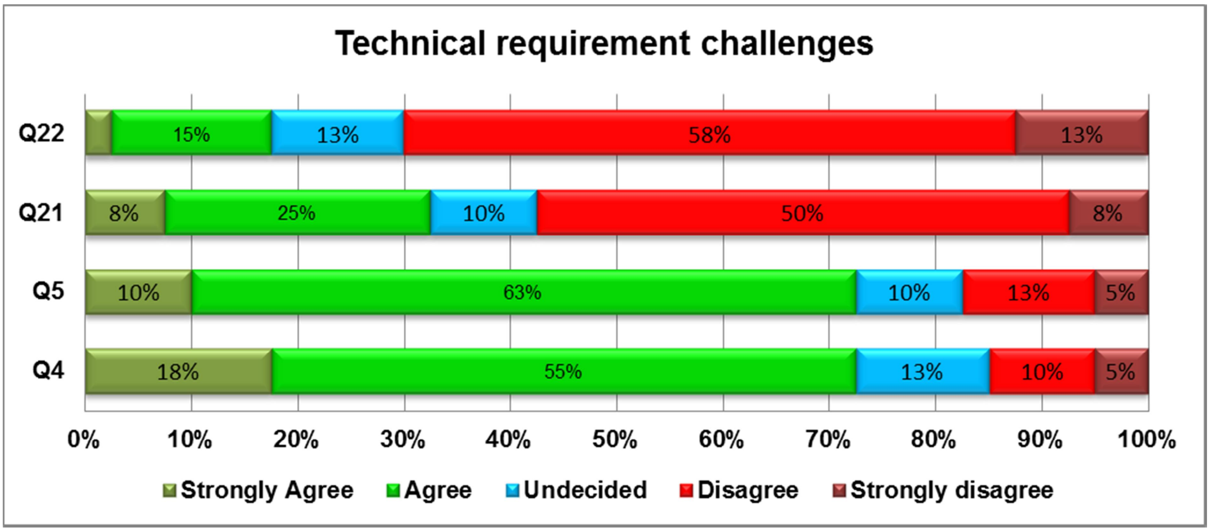
Figure 4.3 Responses of project delays and use of unplanned resources challenges (Source: Researcher's own construction)

Hence, by evaluating responses to these questions shown in Figure 4.3, it can be established that the use of unplanned resources and project delays do occur in the execution of Defence technology R & D projects. Literature has confirmed that defence technology R & D activities are a risky and are an expensive process with some major weapon systems costing billions of dollars and taking between 10 to 20 years to be completed (Jha, 2009). Moreover, defence technology R & D project activities require a costly setup and extended timescales to research and develop military technology (Defence Review, 2014). It can be argued that due to these risks, the majority of the respondents strongly believed that it was difficult to foresee all the resources to be utilised or any deviations from time schedules during the execution of defence technology R & D projects at the beginning of the project.

However, literature has cautioned that in today's environment of reduced defence budget, the DOD can no longer afford the extensive time delays and increased costs that R & D projects have experienced (Mandelbaum and Reed, 2007). Defence technology R & D budgets are being significantly reduced in South Africa and this means that alternate methods need to be investigated to ensure that the resources which available are utilised optimally (Le Roux, 2004). Further questions in the survey aimed to clarify the cause of these project delays and use of unplanned resources.

4.3.1.2 Technical requirements Challenges

It is customary to review and adjust unclear technical requirements at any phase within defence technology R & D projects to ensure designs are successfully completed (Armscor, 2003). However, late phase requirement changes may result in time consuming modifications to the design (Thompson, 2015). The group of questions within this section aimed to verify if unclear technical requirements and late changes to these requirements do occur.



Question	Median	Mode	Question	Median	Mode
Q4	Agree	Agree	Q21	Disagree	Disagree
Q5	Agree	Agree	Q22	Disagree	Disagree

Figure 4.4 Responses to technical requirement challenges (Source: Researcher's own construction)

According to Figure 4.4, the respondents confirmed the following,

- Question 4: Technical requirements are not clearly defined before development commences which results in redesign (73% Agreed to Strongly Agreed).
- Question 5: Review of technical requirements during the development phase that leads to redesign of the concept is acceptable (73% Agreed to Strongly Agreed).

According to Figure 4.4, the respondents disagreed to the following,

- Question 21: Requirements to develop a concept are clearly defined before development occurs (58% Disagreed to Strongly Disagreed).
- Question 22: Review of technical requirements during development phase is unacceptable as it could mean redesign of the concept (71% Disagreed to Strongly Disagreed).

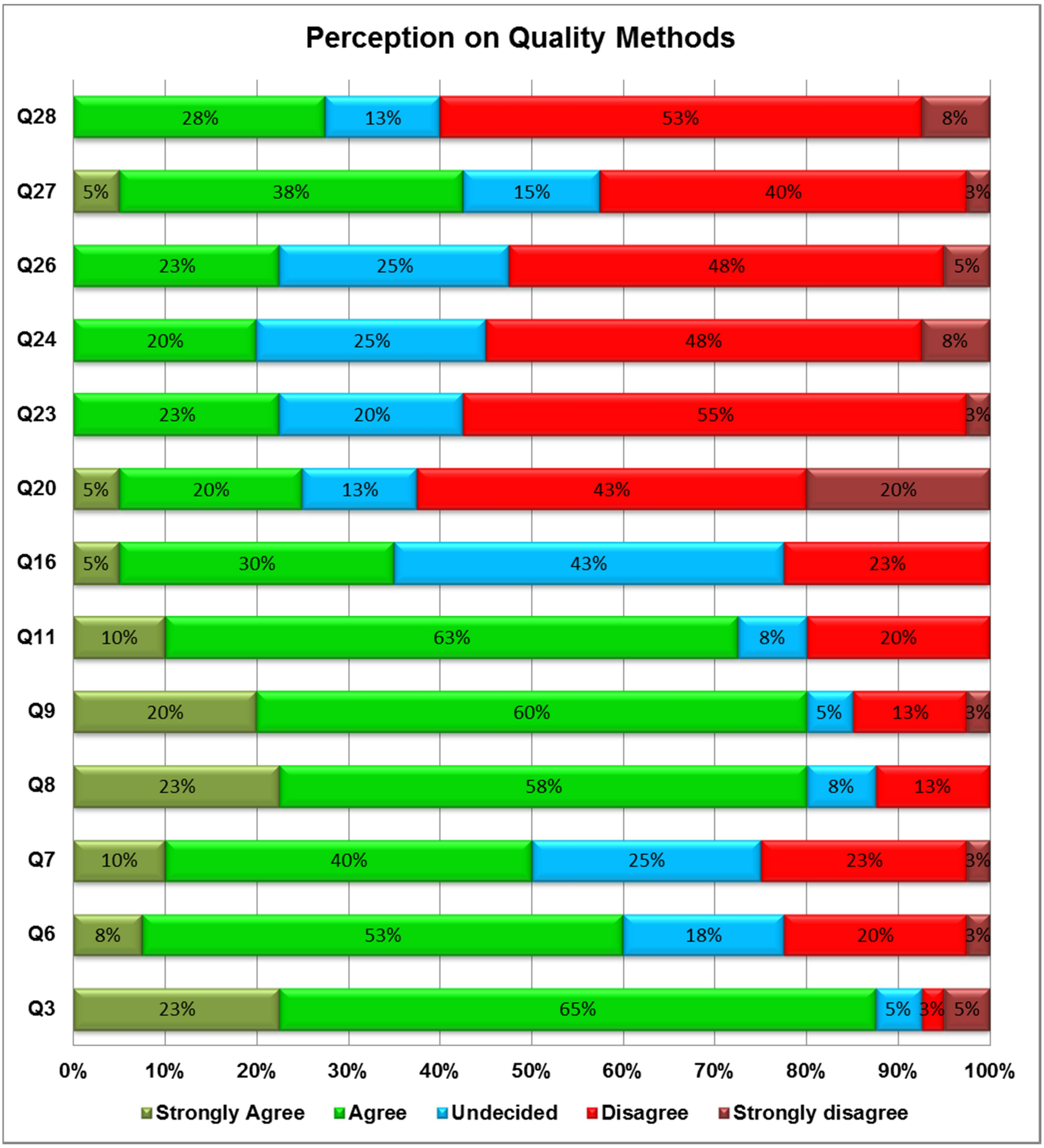
Hence, by examining the responses to these questions, it can be deduced that technical requirements are not clearly defined before commencement of defence technology R & D project execution eventually resulting in redesign activities. Moreover, the results of the survey have also highlighted that review to technical requirements late during the development phase are accepted even if it entails redesign of the concept. These sentiments are acknowledged by the Defence Industry in general where continuous review and adjustment of technical requirements are necessary to ensure deliverables are completed (Armscor, 2003). Literature has cautioned that the R & D project team should take the time to clearly understand the customer requirements to avoid major downstream changes (Yang and El Haik, 2003). Literature has further revealed the problem with late requirement changes that result in major modifications to the design (Thompson, 2015). Furthermore, misinterpreted or unclear requirements can increase the time required to complete a project (Soni and Acharya, 2018). Therefore, it can be accepted that unclear requirements and late adjustment of requirements culminate in redesign activities. Section 4.3.1.4 aimed to establish a link between redesign and project delays and the use of additional resource challenges.

4.3.1.3 Perception on Quality Methods currently used

Various literature have identified several popular methods to optimise designs which are Trade Off analysis, Trial and Error, increase test sample size, post deliverable quality inspection and use of expensive components (Armscor, 2003; Altshuller, 2007; Shiu et al. 2013). However, it is apparent that these traditional quality methods are time consuming and costly on technology R & D projects (Altshuller, 2007; Mehta, 2014; Shiu et al. 2013). Moreover, researchers have emphasised that common quality methods that are designed for repetitive manufacturing processes may create rigidity and stifle creativity if applied to non-repetitive tasks of technology R & D projects (Boyle, 1999; Smailagic and Smailagic, 2014; Thomke and Reinertsen, 2012; Zala, 2015). Thus, the survey will investigate whether traditional quality methods identified in literature are commonly used during the execution of defence technology R & D projects and also whether the project team supports the use of flexible quality tools that embrace the non-repetitive and non-standard tasks of defence technology R & D projects.

According to Figure 4.5, the respondents agreed to the following,

- Question 6: The method of Trade Off analysis is practised to optimise a concept (61% Agreed to Strongly Agreed).
- Question 7: Trial and Error method is commonly applied to improve a design (50% Agreed to Strongly Agreed).
- Question 8: Selection of the best design should be confirmed by evaluating all designs through comparative testing (81% Agreed to Strongly Agreed).
- Question 9: Increasing the number of test samples is a common method to improve confidence in test data of the design (80% Agreed to Strongly Agreed).
- Question 11: Post deliverable quality inspection may result in corrective action (73% Agreed to Strongly Agreed).
- Question 3: Quality methods should be flexible to accommodate varying defence technology project execution processes (88% Agreed to Strongly Agreed).



Question	Median	Mode	Question	Median	Mode
Q3	Agree	Agree	Q20	Disagree	Disagree
Q6	Agree	Agree	Q23	Disagree	Disagree
Q7	Agree	Agree	Q24	Disagree	Disagree
Q8	Agree	Agree	Q26	Disagree	Disagree
Q9	Agree	Agree	Q27	Undecided	Disagree
Q11	Agree	Agree	Q28	Disagree	Disagree
Q16	Undecided	Undecided			

Figure 4.5 Responses to Quality methods (Source: Researcher's own construction)

According to Figure 4.5, the respondents disagreed with the following statements,

- Question 23: The method of design Trade Off analysis is seldom practised (58% Disagreed to Strongly Disagreed).
- Question 24: Trial and Error method is least likely to be practised (56% Disagreed to Strongly Disagreed).
- Question 26: Large sample tests to improve accuracy in test results are overrated (53% Disagreed to Strongly Disagreed).
- Question 28: Post deliverable quality inspection ensures that no further corrective action may need to occur (61% Disagreed to Strongly Disagreed).
- Question 20: Stringent quality methods can be applied as defence technology project execution processes are standard in nature (63% Disagreed to Strongly Disagreed).

From the survey, respondents confirmed that methods of Trade Off analysis, Trial and Error, multiple comparative testing, large sample size testing are practised within defence technology R & D project execution. Unfortunately, literature has revealed the inefficiency of these methods to optimise designs. Yang and El Haik (2003) admitted that the problem associated with Trade Off analysis solutions is that it does not eliminate the technical contradiction in the design, but rather softens them, thus retaining the harmful action in the system. Thus Shiu et al. (2013) observed that the disadvantage with Trade Off analysis is the frequently seen situation where the improvement of a quality characteristic may cause the deterioration of another quality characteristic. Moreover, they indicated that by using Trade Off analysis, the R & D project team conducts modifications to the design to improve that characteristic. Thus, is can be established that Trade Off analysis method practised by the defence technology R & D project team is not an efficient method and that it maintains harmful contradictions in a design.

Regarding the use of Trial and Error experimental method, the majority of the respondents agreed that this method is practised to optimise designs. Contrary to this belief, literature has discovered that this method is inefficient. Altshuller (2007) asserted that the problem with the Trial and Error method is that the method moves back and forth developing various searching concepts (SC) to optimise a design. Shiu et al. (2013) added that this approach leads to redesign of the concept until the design meets the requirements. Mehta (2014) warned that for defence technology R & D projects, there is neither room for excessive timescales nor Trial and Error testing as the delivery of successful results to the client is becoming increasingly high.

The survey confirmed that design selection is applied by evaluating all designs through comparative testing. Turner (2015) highlighted the advantage of applying comparative testing with its ability to gather lots of data by comparing different designs. However, he also admitted that testing multiple designs invariably makes the method a little more complex to run and limits the number of tasks one can cover across the different designs. Furthermore, the disadvantage as outlined by Turner (2015) is that there is potential for some bias as the project team is being exposed to one design before the other.

The respondents did concur that large sample testing is a common method to improve confidence in test data of the design. Shiu et al. (2013) stated that to ensure successful inspections and testing, the R & D project team requires increased test samples sizes to improve the problem detection rate on designs. Though the use of large sample size tests may improve the quality of the design concept, it does, however, require a large amount of time and resource. As reported by Levine et al. (2001) when four or more factors are to be evaluated often, the experiment becomes costly or impossible to simultaneously run all treatment combinations. Hence, a more economical way of testing the treatment combinations should be used so that the experiment can achieve meaningful results.

With regards to post deliverable quality inspection methods being applied during the execution of defence technology R & D projects, the respondents have confirmed that quality methods are applied upon completion of a deliverable. Yang and El Haik (2003) outlined that organisations who follow this method usually suffer from high development costs, longer time to market, lower quality levels and marginal competitive edge. Secondly, respondents admitted that corrective action activities can occur once post deliverable quality inspection has been completed. This perception is in line with the defence technology R & D project management practice that states that necessary corrective actions are recommended after a quality inspection has revealed non-compliance with the requirements (Armscor, 2003).

By examining responses to both Questions 3 and 20, it can be concluded that quality tools should be flexible in Defence technology R & D projects execution. Literature reviewed has emphasised that technology R & D activities are non-repetitive; unpredictable and unique in nature (Thomke & Reinertsen (2012). As such, quality methods such as control charts that may be effective in a highly repetitious environment might not be suited for technology R & D projects (Boyle, 1999). A flexible quality method is necessary as it allows the research scientist or research engineer the autonomy to think of innovative military technologies for the SANDF. Hence, flexible quality tools need to be investigated which is strongly supported as revealed by the survey.

According to Figure 4.5, the respondents were unsure of the following,

- Question 16: The use of expensive materials to rapidly optimise a design is acceptable (43% were Undecided, Median and Mode were Undecided).
- Question 27: Quality inspection methods applied at the completion of a deliverable is insufficient (43% Disagreed to Strongly Disagreed and 43% Agreed to Strongly Agreed, Median was Undecided, Mode was Disagreed).

The respondents view on the use of expensive materials to optimise a design was inconclusive as the majority of the respondents felt unsure as to whether expensive materials to optimise a design is acceptable and thereafter the same group felt that it is unacceptable to use expensive materials to rapidly optimise a design. Moreover, responses were split as to whether post deliverable quality inspection methods were sufficient or not. Despite the respondents being inclined to disagree (46% disagreeing to strongly disagreeing), regarding post deliverable quality inspection methods being sufficient, the result is inconclusive. Regardless of the mixed perception to this question, respondents have already highlighted that post deliverable quality inspection will lead to corrective action activities. Furthermore, the uncertainty on post deliverable quality inspection methods being adequate to optimise defence technology project execution highlights the urgent need to develop clearly defined quality methods for defence technology R & D project execution.

From the analysis of quality methods practiced, is can be confirmed that large sample size testing, multiple comparative testing, Trade Off analysis, Trial and Error and post deliverable quality inspections are acceptable in the execution of defence technology R & D project execution. It was highlighted in literature that the common activity that resonates with these methods is the need for corrective action through redesign activities to optimise designs. The next group of questions aims to establish a link between redesign and project delays and use of additional resources.

4.3.1.4 Redesign Challenges

It was established from earlier questions that review and unclear technical requirements, methods of large sample size tests, multiple comparative testing, Trade Off analysis, Trial and Error and post deliverable quality inspection are practised in defence technology project execution to optimise designs. However, these methods resulted in redesign activities. The next group of questions investigated the problems that redesign creates when it occurs.

According to Figure 4.6, respondents agreed to the following statements,

- Question 12: Redesign of a concept requires replacement of components (80% Agreed to Strongly Agreed).
- Question 14: Redesigning increases the risk of completing the project within the planned deadline (83% Agreed to Strongly Agreed).
- Question 15: Engineering changes to the design will require additional materials. (56% Agreed to Strongly Agreed).

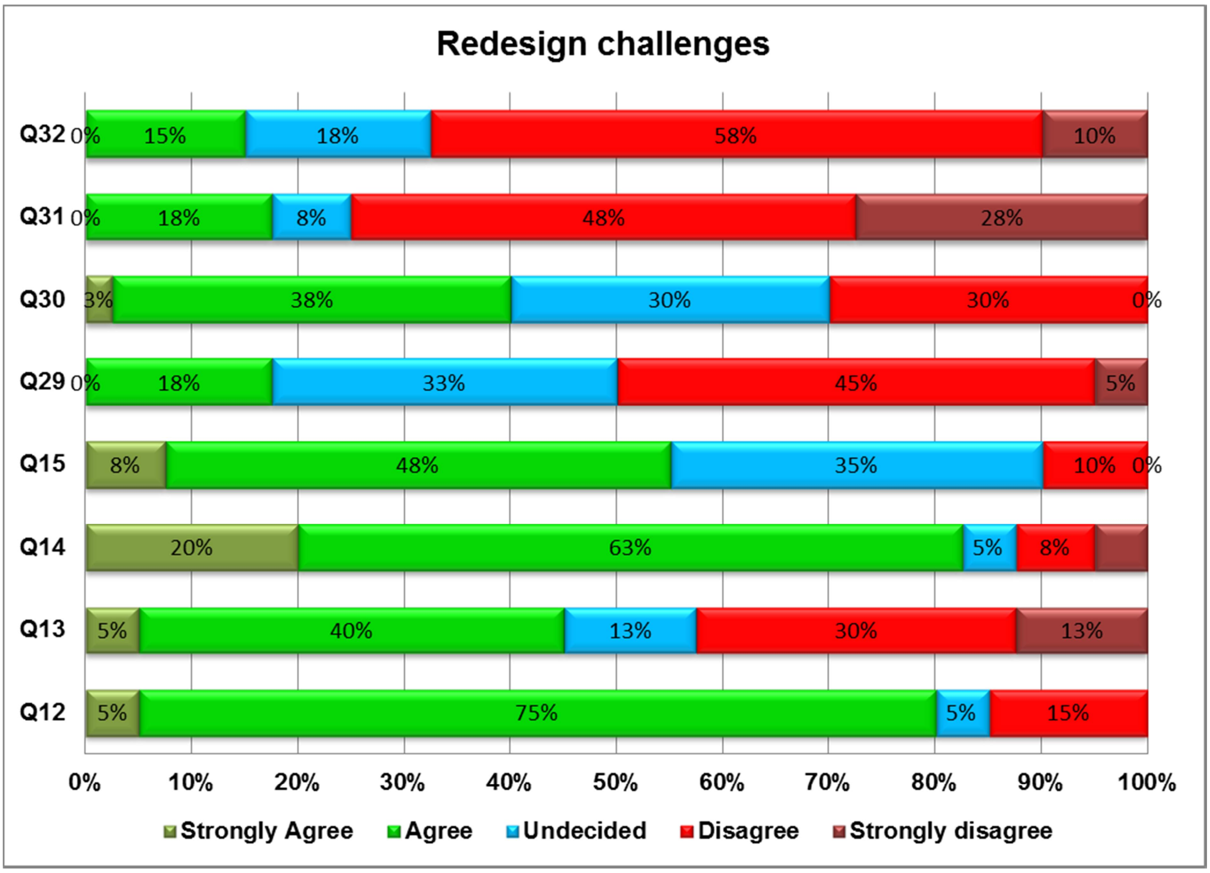
According to Figure 4.6, the respondents disagreed with the following statements,

- Question 29: Redesign may not require replacement of components (50% Disagreed to Strongly Disagreed).
- Question 31: There is no risk in redesign that will result in delaying the project. (76% Disagreed to Strongly Disagreed).
- Question 32: Engineering modifications to the design may not require extra resources. (68% Disagreed to Strongly Disagreed).

According to Figure 4.6 the respondents were uncertain about the following,

- Question 13: During redesign, components that were replaced may never be re-used on another design (43% disagreed to Strongly Disagreed and 45% Agreed to Strongly Agreed, Median was Undecided).
- Question 30: Uniquely manufactured components that were discarded during redesign could be reused on another project (Mode was Undecided).

Therefore, based on the responses from the survey, it can be established that redesign activities result in the use of additional materials, replacement of components and project delays during the execution of defence technology R & D projects. However, respondents were uncertain as to whether components specially manufactured for a concept may never be reused during redesign. Gryna (2001) admitted that redesign is problematic as it leads to costs of failure to meet customer requirements and needs. The problem of redesign stems from poorly defined technical requirements and current quality tools which requires the need for additional unplanned resources and project delays.



Question	Median	Mode	Question	Median	Mode
Q12	Agree	Agree	Q29	Disagree	Disagree
Q13	Undecided	Agree	Q30	Agree	Undecided
Q14	Agree	Agree	Q31	Disagree	Disagree
Q15	Agree	Agree	Q32	Disagree	Disagree

Figure 4.6 Responses to redesign challenges (Source: Researcher's own construction)

4.3.1.5 Chi-Square Test for Association Analysis

The previous analysis indicated that respondents agreed that the practise of quality methods of review of technical requirements, Trade Off analysis, Trial and Error, large sample testing, multiple comparative testing and post deliverable quality inspections do occur in defence technology R & D Project execution. In addition, respondents confirmed that redesign activities lead to challenges of project delays and use of unplanned resources occur. The chi-square test for association will determine whether statistically significant relationships exist between challenges and review of technical requirements, Trade Off analysis, Trial and Error, large sample testing, multiple comparative testing and post deliverable quality inspections methods.

For the chi-square test analysis, Hall (2018) recommended simplifying the response categories by combining the response categories in the Likert scale of “agree” and “strongly agree” responses into one category and the “disagree” and “strongly disagree” into another. He added that this would give three categories of responses being agree, disagree and undecided. Similarly, Nxopo (2011) also suggested combining the responses of the groups “Agree” and “Strongly Agree” into one group” and combining the groups who “disagree” and “strongly disagree” into one group.

Questions were analysed from the first half of the questionnaire (Section 2 Questions 1 to 17) due to the fact that the second half questions (Section 2 Questions 18 to 34) measured the same variables as the first half. The correlation between both halves was measured to be good as shown in Section 4.2.2. This implied that the responses between both halves were consistent. The following questions in Table 4.2 were cross-tabulated using chi-square test for association and revealed relationships between the questions. The critical value of 9.488 was selected based on 4 degrees of freedom and a level of significance of 0.05. Hall (2018) explained that the chi-square statistic compares respondents' actual responses to questions with expected answers to assess the statistical significance of a given hypothesis. The subsequent hypothesis was used during the analysis:

Hypothesis

H_0 = The variables in the questions are independent of each other

H_1 = The variable in the questions are not independent of each other

Table 4.2 Chi-Square Test for Association between Selected Variables (Source: Researcher's own construction)

Questions	Association under Investigation	X^2	p-value
Q1 & Q5	The review of technical requirements are allowed and the need for additional unplanned resources.	10.779	0.02642
Q2 & Q8	Project time schedules are extended and the practice of multiple comparative testing.	13.735	0.01363
Q6 & Q12	The practice of Trade Off analysis method and redesign activities resulting in replacement of components	16.345	0.00750
Q6 & Q14	The practice of Trade Off analysis method and redesign activities resulting in project delays	12.695	0.03446
Q7 & Q14	The practice of Trial and Error and redesign activities resulting in project delays	10.600	0.02528
Q8 & Q12	The practice of multiple comparative testing and redesign activities resulting in replacement of components	13.433	0.00692
Q9 & Q14	The practice of large sample testing and the redesign activities resulting in project delays	19.171	0.00662
Q11 & Q12	The practice of post deliverable quality methods and redesign activities resulting in replacement of components	18.116	0.00876
Q11 & Q14	The practice of post deliverable quality methods and redesign activities resulting in project delays	18.142	0.00976

The results of the analysis in Table 4.2 showed the chi-square test values are greater than the critical value of 9.488. The results also revealed that p-values were less than the level of significance (0.05) hence the H_0 hypothesis was rejected. As stated by Nxopo (2011), results will be regarded as significant if the p-values are smaller than 0.05, because this value is used as a cut-off point in most behavioural science research. Therefore, the alternate H_1 hypothesis was accepted where the variable in the questions is not independent of each other. The chi-square and p-values indicated statistically significant relationships that existed between the variables and thus the following conclusions can be drawn within defence technology R & D project execution:

- There is an association between the review of technical requirements and need for additional unplanned resources.

- There is an association between project time schedule extensions and the practice of multiple comparative testing.
- There is an association between the practice of Trade Off analysis method and redesign activities resulting in replacement of components.
- There is an association between the practice of Trade Off analysis method and redesign activities resulting in project delays.
- There is an association between the practice of Trial and Error and redesign activities resulting in project delays.
- There is an association between the practice of multiple comparative testing and redesign activities resulting replacement of components (additional resources).
- There is an association between the practice of large sample testing and the redesign activities resulting in project delays
- There is an association between the practice of post deliverable quality methods and redesign activities resulting replacement of components (additional resources).
- There is an association between the practice of post deliverable quality methods and redesign activities result in project delays.

From the chi-square analysis, it can be confirmed that the practice of quality methods of review of technical requirements, Trade Off analysis, Trial and Error, large sample testing, multiple comparative testing and post deliverable quality inspections are linked to redesign activities culminating in challenges of project delays and use of additional unplanned resources.

4.3.2 Results and Analysis of Section 3 and 4

This section of the study presents results from Section 3 and Section 4 that requested respondents to voluntarily list additional quality methods as well as other challenges experienced within defence technology R & D project execution respectively.

4.3.2.1 Question 35 (Section 3)

Question 35 requested respondents to select from a list of quality tools that are applied in the execution of defence technology R & D projects. The selection originated from reviewing these methods in Chapter 2.

The following can be noted from the survey results.

- Methods of Brainstorming and Design Review are shown to be popular amongst respondents with over 70% of them confirming the use of these methods.
- Design of Experiments and DFMEA are also known methods amongst respondents with over 50% of the replies confirming the use of these methods.
- The least popular methods are QFD, Pugh selection, Axiomatic Design, TRIZ, Taguchi Robust Design, P Diagram and Ishikawa Cause and Effect being less than 45%

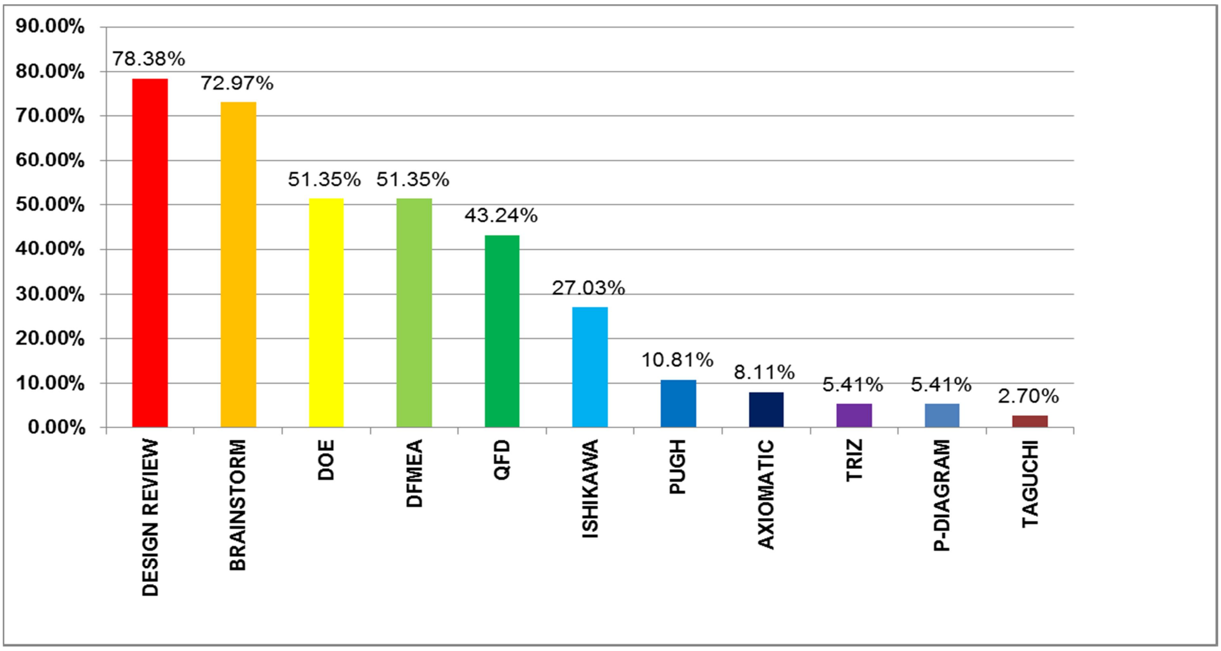


Figure 4.7 Quality Methods currently applied (Source: Researcher's own construction)

Referring to Figure 4.7, respondents strongly advocated the use of Design Reviews and Brainstorming. Yang and Haik (2003) acknowledged that design reviews are used to evaluate several design alternatives in order to make a final determination on which concept will be used. They further reasoned that design reviews can be used to detect deficiencies in designs. Besides design reviews, Brainstorming is considered a useful tool by both respondents of defence technology R & D project execution and literature. The Mind Tool Limited (2009) confirmed that brainstorming is a popular tool to generate creative solutions to solve a problem and when utilised in a team method, it brings the diverse experience of all team members into play which increases the opportunity to find better solutions. From literature, it was identified that both these methods provide support to other quality tools such as TRIZ and DFMEA.

The survey showed that Design of experiments (DOE) is a popular method. However, examination of this method during the literature review has revealed that conventional DOE is known to be very complicated and costly (Ghani et al. 2013). Further research has shown that although conventional DOE will provide more information, it will require more experimental runs (Yank and El Haik, 2003). Hence, due to resource and time schedule constraints, an alternative to costly and complex methods should be considered for defence technology project execution.

In contrast, methods of QFD, Pugh selection, Axiomatic Design, TRIZ, Taguchi Robust Design, P Diagram and Ishikawa Cause and Effect are considered least popular amongst respondents to be applied in defence technology R & D project execution. This response is not unexpected, as contradictory methods of Trade Off analysis, Trial and Error, multiple comparative testing, large sample size testing are currently practised within defence technology R & D project execution as pointed out in section 4.3.1.3. Literature has maintained that large sample size testing, Trade Off analysis and Trial and Error to optimise design concepts are time consuming and costly on technology R & D projects. Whereas methods of QFD, Pugh selection, Axiomatic Design, TRIZ, Taguchi Robust Design, P Diagram and Ishikawa Cause and Effect are inclined towards efficient use of time and resources. Therefore, a quality tool framework that shows the potential of Pugh selection, Axiomatic Design, TRIZ, Taguchi Robust Design, P Diagram and Ishikawa Cause and Effect methods to efficiently and economically optimise defence technology R & D project execution is needed and should be developed.

4.3.2.2 Optional Question 36 (Section 4)

Question 36 was an optional open-ended question that requested respondents to list other quality tools currently being implemented to optimise defence technology R & D project execution. Taylor-Powell and Renner (2003) recommended the following in categorizing collected information:

- Identify patterns or themes
- Organise themes or patterns into coherent categories.

To also show important categories, Taylor-Powell and Renner (2003) also suggested counting the number of times a particular theme arises as these counts can reveal general patterns in the data. Based on these recommendations, methods identified during the review of question 36 were grouped into the following categories:

- **Simulation and Modelling**: Matlab, Monte Carlo
- **Manufacturing Techniques**: Rapid 3D printing, build proof of concept
- **Testing and Evaluation**: Testing in operational environment, Human-Machine Interface evaluation
- **Analysis Tools**: Requirement analysis tools Core Software Design Principles, Dynamic Object Oriented Requirements System (DOOR), Systems Architect, Mind Manager, Functional Hazard Analysis (Extended FMEA) and Fault Tree Analysis. Use of Architectural Mitigation Techniques, Objective matrix, design reviews, failure mode and effect analysis (FMEA)
- **Management tools**: MS Project, Project Management Book of Knowledge (PMBOK), Contracts, Request for Information

The information collected on the above categories are shown in a bar diagram in Figure 4.8. Taylor-Powell and Renner (2003) proposed using a diagram to show all the results.

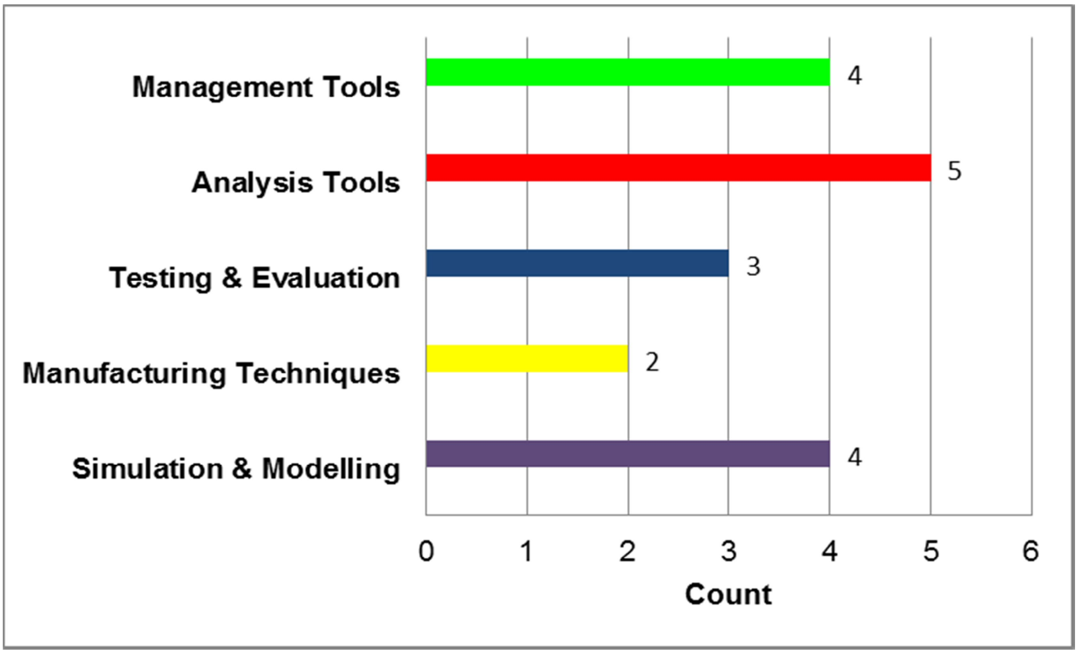


Figure 4.8 Other Quality Methods applied in Defence Technology R & D project Execution (Source: Researcher's own construction)

Simulation and modelling tools are essential in any technology R & D project as revealed by the respondents. Yang & El Haik (2003) stated that modelling and simulation programs can be applied to assess and improve the design concept so as to achieve the best possible functionality at the lowest possible cost. They added that because of the high investment required to develop the actual hardware prototype, computer simulation models are used in conjunction with Taguchi Robust design method rather than actual physical tests. Therefore, simulation and modelling tools can be used as an evaluation method in conjunction with Taguchi methods to optimise designs in defence technology R & D project execution.

Several respondents highlighted the need to manufacture prototypes to optimise designs. Yang and El Haik (2003) emphasised that in product design, prototypes are built to test and validate the design. They admitted that this process of physical prototyping is more costly and more time consuming and instead recommended the use of simulation and modelling to evaluate designs. This study does not ignore this important aspect of manufacturing prototypes in technology R & D projects, it has however underlined the need to conduct a thorough analysis of designs using systematic quality tools identified in the literature review before building and evaluating a prototype since manufacturing a prototype is expensive and time consuming.

The respondents revealed the need for testing and evaluation in defence technology R & D project execution specifically evaluating designs in an operational environment. Literature defined environmental operating conditions as noise (uncontrollable) factors and control factors. Park, Hwang, Lee and Lee (2006) stated that a block diagram (P diagram) can be used to identify both noise and control factors and its interaction with design parameters and functional requirements. Furthermore using the orthogonal arrays identified in the Taguchi Robust design method, the design can be evaluated under operational conditions at reduced cost and time. Shiu et al. (2013) indicated that orthogonal arrays test the interaction of both control factors and noise factors. Thus, this study supports the view of respondents that designs should be optimised by evaluating the concept in its operational environment. Methods such as P diagram along with Taguchi Robust design methods ensure operational conditions are considered when designs are evaluated.

Respondents identified various analysis methods. However, several of these methods were licenced software which implies that funds are required to purchase and maintain the use of these analysis methods. Furthermore, respondents repeated methods such as Design reviews and FMEA that were reviewed in Chapter Two and this confirmed the importance of these methods in defence technology R & D project execution. Method of Fault Tree Analysis (FTA) was mentioned as a tool to optimise defence technology project execution. Schenkelberg (2016) defined fault tree analysis (FTA) as a logical, graphical diagram that lays the possible faults and combinations of faults, within the subsystems, components, assemblies, software and parts comprising the system that may lead to the top-level unwanted fault condition. He added that FTA shows the many possible cause-and-effect paths to a specific fault condition. Thus, this FTA method warrants further investigation into its processes and it may have the potential to be included into a framework of quality methods to optimise defence technology R & D project execution.

Moreover, respondents identified the use of management tools to optimise defence technology R & D project execution. However, management tools such as PMBOK and contracting are high level guides, whereas this study is investigating challenges on the lower level research and development activities of defence technology R & D projects. Hence, these methods are beyond the scope of this research which is examining quality methods on the lower level execution processes rather than higher order project management and contracting processes.

4.3.2.3 Optional Question 37 (Section 4)

The respondents were requested to freely identify other challenges which may lead to project delays and the use of unplanned resources. Several respondents listed higher level management, operational and political challenges that were out of the scope of the research study such as:

- Lack of maintenance of test equipment,
- Unavailability or high cost of military platforms for tests due to obsolescence,
- Lack of transformation,
- Lengthy logistics support processes,
- Poor project management,
- Change management issues,
- Lack of diversity in suppliers,
- Lack of focus and synergy within SANDF,
- Lack of human capital and expertise in defence technology projects,
- Delays in funding approval and
- Delays in acquisition of components using lengthy state acquisition rules and regulations.

It is important to note these concerns afore mentioned as future studies may need to investigate these areas. The following challenges were highlighted that were within the scope of this study:

- Requirements not defined clearly and scope creep that results in longer development time; and
- Lack of critical technical requirements that need to be achieved by the technology concept.

Respondents have reiterated challenges with “unclear technical requirements”. These issues were highlighted in Section 4.3.1.2 where the majority of the respondents confirmed that technical requirements were not clearly defined before defence technology project execution commences. Hence, this results in redesign activities. Furthermore, respondents acknowledged the failure to define all critical technical requirements to assess the performance of the technology concept. It was noted that translation and prioritisation of critical SANDF requirements into clear design requirements or technical requirements are necessary for the development of effective military technologies. Therefore, failure to recognise core technical requirements at the onset of the defence technology R & D project execution will have a negative effect on the design of effective military concepts.

4.4 Summary of the chapter

In this chapter, reliability was verified and the results were found to be “good”. Validity of the results were also “good” as from the survey it was reasoned that challenges of project delays and use of unplanned resources emanated from ambiguous technical requirements and inefficient quality methods within defence technology R & D project execution. Hence, the survey instrument adequately measured the variables (units of analysis) identified in Figure 3.3. Furthermore, being a single case study on defence technology R & D Project in South Africa, the findings from the survey confirmed what was identified in established theory on challenges in technology R & D projects which include continuous project delays and the use of resources.

An analysis of the results of each section was then presented and discussed. Section 1 of the questionnaire was used to profile the respondent according to the respondent’s designation. It was found that the majority of respondents were R & D project managers. Section 2 was divided into 4 subsections which formed the bulk of the questionnaire and posed mandatory questions relating to challenges and quality methods in defence technology R & D projects as identified in literature. The results yielded that the practice of quality methods of review of technical requirements, Trade Off analysis, Trial and Error, large sample testing, multiple comparative testing and post deliverable quality inspections are linked to redesign activities culminating in challenges of project delays and the use of additional unplanned resources. The findings of all sections were compared to and confirmed with existing theory in literature (conceptual framework). Section 3 of the questionnaire required respondents to select from a list of quality methods. The findings revealed the poor adoption of methods of QFD, Pugh selection, Axiomatic Design, TRIZ, Taguchi Robust Design, P-diagram and Ishikawa Cause and Effect which are tailored for technology R & D project activities. Section 4 comprised two optional questions to identify other challenges, as well as the use of further quality methods in defence technology R & D project execution. The findings of this section confirmed issues that were previously highlighted in earlier sections. Moreover, of all the tools listed by respondents, fault tree analysis stood out to be a suitable tool that may be included the quality toolbox framework to optimise defence technology R & D project execution.

Therefore, a gap of knowledge exists in the South African defence technology R & D project execution environment where the use of suitable quality methods is virtually absent. Instead, only a handful of methods such as Brainstorming and Design Reviews were identified by the majority of respondents. Unfortunately simply employing these methods to optimise defence technology R & D project execution has shown to be not sufficient to curtail the issues of project delays and the use of unplanned resources. The combination of continual technical requirement changes, the practice of inefficient quality methods plus the lack of use of quality methods designed for technology R & D projects are resulting in continual project delays and the use of unplanned resources. The result of the survey proved that R & D project teams urgently require a rich and diverse selection of appropriate quality methods that will allow them to:

- Reduce changes to technical requirements,
- Eliminate dependence on inefficient methods, and
- Optimise activities at any phase within the defence technology R & D project execution.

In the next chapter, the conclusion and recommendations based on the findings of the research will be discussed and a framework to optimise defence technology project execution will be proposed.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

This chapter encapsulates the research study by reviewing each chapter namely background of research, literature review, research methodology and results of the survey. Findings from the literature review and survey were used for the development of a functional quality toolbox framework to optimise defence technology R & D project execution. The effectiveness of this practical framework was evaluated during a perception study. The study objectives are revisited and discussed. Finally, conclusions, recommendations and future research in defence technology R & D project execution will be proposed.

The next section summarises the motives that led to this research study.

5.1 Background to the Research Problem Summation

This section summarises the rationale for this research study by addressing the key issues within the defence technology R & D project execution. Many countries are questioning the effectiveness of current defence technology R & D activities and its methods in generating quality technologies efficiently (Jha, 2009). The background to the study highlighted the following methods that result in project delays and the use of unplanned resources:

a. Late review and subsequent changes to technical requirements during R & D technology projects may lead to redesign activities. Furthermore, literature highlighted that the effect of these late changes to requirements may result in failure to complete the project on time and within budget (Thompson, 2015).

b. Post deliverable quality methods that are practised in defence technology R& D projects may lead to corrective action such as redesign of the task to resolve the problem. The effect of these activities of redesign culminates in delays and the utilisation of additional funds, scarce resources such as labour and material (Yang and El Haik, 2003; Gryna, 2001).

c. The use of the testing cycle process is a popular method to improve quality in technology R & D projects (Taguchi, 2012; Shiu et al. 2013; Wingate, 2013). Unfortunately, this process condones continuous iterations to the design by using methods such as large sample size testing, Trade Off analysis, Trial and

Error, multiple comparative testing and the use of superior materials and components to optimise the design (Altshuller 2007; Shiu et al. 2013).

Hence due to shrinking investments into defence technology R & D projects, problems of R & D project delays and excessive use of scarce resources can no longer be accommodated (Jha, 2009; Mehta, 2014). Therefore, the focus of the study was to reduce the above inefficiencies that are perceived to result in R & D project delays and the use of unplanned resources within the South African Defence Industry particularly in the defence technology R & D project execution environment by implementing appropriate quality tools that will reduce these inefficiencies.

A review of pertinent literature on various quality methods that are designed for technology R & D projects was then conducted.

5.2 Literature Review Summation

This section condenses the various quality methods studied during the literature review. A review of literature in Chapter 2 revealed limited or no focus in the area of quality in defence technology R & D projects and thus literature reviewed in this chapter predominately originated from the commercial and civil technology R & D project environment.

Various sources highlighted clear differences between activities of technology R & D project activities and manufacturing. It was emphasised that proven quality methods in manufacturing might not adequately address the needs of technology R & D projects because R & D activities are non-repetitive and non-standard in nature (Armscor, 2003; Thomke and Reinertsen, 2012). Failure to recognise this has resulted in the application of rigid quality control methods causing problems including projects delays (Thomke and Reinertsen, 2012). Therefore, it is safe to say that a new mind-set has to be adopted when selecting quality tools appropriate for defence technology R & D project execution activities. This shift in thinking required the need to identify quality methods that were systematic, logically laid out, simple and efficient to use, low cost, not burdensome in terms of more paperwork and embrace the flexible method of defence technology R & D project execution activities.

The various quality methods investigated followed the approach of being flexible, systematic and logical. These methods included Quality Function Deployment, Axiomatic Design, TRIZ inventive problem solving, Pugh Selection Matrix, Design Failure Mode Effect Analysis, Brainstorming, Design Review, Ishikawa Cause and Effect, P Diagram and Taguchi Robust Design. Research indicated that these methods can provide an alternative to the current approach of post deliverable quality inspection, large sample size testing, Trade Off Analysis, Trial and Error testing, multiple comparative testing and the use of superior materials and components to optimise the design (Yang and El Haik, 2003; Yang and Zhang, 2000). Further examination of these methods revealed that the majority of these methods can be applied early during the R & D project execution before the design concept is developed and evaluated thus saving time and cost (Banciu and Draghici, 2003; Yang and El Haik, 2003). Moreover, these quality methods have a mutual bond amongst themselves as shown in Figure 2.12. It can be perceived that this connection is paramount in developing a useable and logically laid out Toolbox framework which can be applied by the defence technology R & D project execution team.

The background to this research and the review of literature above laid the foundation for the development of the questionnaire used in this study. The questionnaire was administered to the South African defence technology R & D project execution environment. The design of this questionnaire and the research methodology adopted for this study is summarised in the next section.

5.3 Research Study Methodology Summation

This section summarises Chapter 3 of the case study research methodology that was adopted for this research and the subsequent design and the pilot testing of the survey questionnaire. Processes for the succeeding main study and final perception study on the framework developed are mooted in this section.

The research methodology adopted was an embedded single case study approach. As part of this methodology is the investigation of units of analysis to which the research problem refers. The perceived problem being a review of requirements and the use of current quality methods are leading to redesign activities culminating in project delays and the use of unplanned resources within defence technology R & D project execution.

The initial research objective was to identify using a survey, challenges experienced by project teams, as well as suitable quality tools that are applied during the execution of defence technology R & D projects. The variables under investigation stemmed from the unit of analysis identified in Chapter 3. The survey questionnaire was designed to investigate these challenges and suitable quality methods as identified from the background to this research and the review of literature. Preceding the main study, work was conducted on the questionnaire to test the effectiveness of the questions in identifying quality challenges and suitable quality methods. The questionnaire was administered to 5 respondents via email. The feedback from the respondents confirmed that questions posed in Section 2 were not detailed enough and could create ambiguity amongst respondents. Secondly, the selection of quality methods in Section 3 to optimise inefficient methods in the execution of defence technology R & D projects may not be familiar to many respondents. Based on these recommendations the questionnaire was reworked to include more clarity as possible in areas where challenges were perceived to occur and a list of definitions was also attached to the questionnaire that explained the function of each quality tool listed. The main study followed the pilot study that was administered to the target audience comprising of R & D Project Managers, SANDF R & D officers, research engineers/scientists and technical support functions within South Africa’s defence technology R & D Project execution environment. Following the main study method, the chapter detailed the process to be used during the perception study on the framework to be developed to optimise defence technology R & D project execution.

Results of the main study survey were then analysed and this is discussed concisely in the next section.

5.4 Survey Results and Analysis Summation

This section summarises the results and analysis of the survey that was detailed in Chapter 4. The results of the survey revealed the lack of appropriate quality methods being implemented in defence technology R & D project execution and the consequent issues of redesign activities that result in project delays and the use of additional scarce resources.

The first study objective of this research was to identify, using a survey, challenges experienced by project teams that are generating redesign activities culminating in project delays and use of unplanned resources during the execution of defence technology R & D projects. The second study objective of this study was to identify suitable quality tools that are applied during the research (definition) and development (design and testing) phase to optimise the execution of defence technology R & D projects. Based on the first and second study objectives of this research, this section summated the results of the survey that was conducted on the respondents from the South African Defence Technology R & D project execution environment. The results were synonymous with existing theory on current quality challenges and quality methods in R & D projects.

According to the results of the survey, the general perception is that project delays and the use of unplanned resources do occur during the execution of defence technology R & D projects. It is accepted that defence technology projects are technically high risk in nature and a high level of uncertainty is expected in its activities (Armscor, 2003). Hence, it can be accepted that technology R & D project teams make use of unplanned resources and tend to extend deadlines during the execution of defence technology R & D projects in order to complete the required design concept.

It is evident from the results of the survey that technical requirements are not clearly defined at the beginning of the defence technology R & D project execution. When posed with an optional question to freely list other challenges that cause project delays and the use of unplanned resources, the respondents reiterated the lack of critical technical requirements being defined as a problem. Furthermore, the survey indicated that a review of requirements for the redesign of the concept is acceptable. In addition, the chi-square test for association showed a strong connection between the review of technical requirements and the need for additional unplanned resources. Drawing on this perception from the survey, it can, therefore, be validated that technical requirements are not clearly defined at the beginning of the defence technology R & D project execution which results in requirements being changed at a later stage and subsequent redesign of the concept.

The results of the survey revealed that respondents advocated the use of the following quality methods to optimise designs:

- Trade Off analysis between design characteristics to optimise a design,
- Trial and Error experimental method,
- Increased size of test samples or test runs to improve designs,
- Multiple comparative testing to evaluate designs, and
- Post deliverable Quality inspection methods.

Literature maintained that these quality methods to optimise designs and concepts are not efficient and are problematic as it leads to redesign activities. Moreover, the chi-square test for association acknowledged a strong link between these quality methods and redesign activities resulting in challenges of project delays and the use of unplanned resources.

The respondents confirmed that the effect of redesign activities during defence technology R & D project execution results in the use of additional resources and project delays. Hence, current quality methods that are applied to optimise designs are resulting in redesign activities. Alternate quality tools need to be considered for defence technology R & D project execution so as to minimise inefficient activities of redesign.

From the above results, it can be summated that challenges of project delays and the use of unplanned resources do occur from ambiguous technical requirements and inefficient quality methods within defence technology R & D project execution. Moreover, the survey further revealed the lack of systematic, logical, efficient and low cost quality tools that are practised during defence technology R & D project execution.

The majority of respondents confirmed the use of only a handful of suitable quality methods for defence technology R & D project execution that being Brainstorming and Design Reviews. The results further confirmed the lack of the use of QFD, Pugh Selection Matrix, Axiomatic Design, TRIZ, Taguchi Robust Design, P Diagram and Ishikawa Cause and Effect methods. The respondents did, however, concur with literature where quality tools should be flexible particularly in defence technology R & D projects execution where activities are non-standard and vary between projects.

The method of Fault Tree Analysis (FTA) was listed as a potential tool to optimise defence technology R & D project execution. Apart from FTA, the remainder of the methods proposed by the respondents were aimed at high level management and contracting processes or required costly software licences. According to Teixeira and Soares (2011), FTA is a top-down process by which a failure event in a project is logically decomposed into possible causes in increasing detail to determine the causes or combinations of causes of the top event. In like manner, Marshall (2012) also noted that FTA is a systematic method of analysis that examines a system from top to down using graphical symbols for ease of understanding. Hence, this method is aligned to this study's object in identifying quality methods that use a systematic and logical approach to optimising defence technology R & D project execution that will deliver superior military technologies to the SANDF.

Marshall (2012) further acknowledged that FTA is used to investigate potential faults, its modes, its causes in designs. Likewise, the DFMEA process reviewed in Chapter 2 follows a similar methodology in identifying and tackling problems early during the R & D technology process. Egerton Consulting (2015) explained that FMEA is a bottom up approach that examines the lower failure modes of components within a design and traces the potential effects of these failure components up to the overall system design. Whereas for FTA, CQE Academy (2016) stated that this method focusses on the top level event and then subsequently determines all of the lower level failure modes that can contribute to the occurrence of that top level event. Figure 5.1 illustrates FMEA as a Bottom-Up technique while FTA as a Top-Bottom technique.

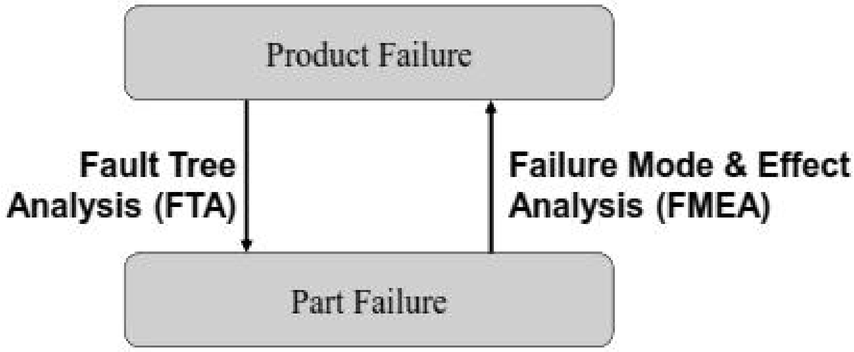


Figure 5.1 Relationship between FMEA and FTA (Source: Marshall, 2012)

Moreover, Egerton Consulting (2015) recommended using FMEA for new technologies and to optimise designs as it is able to analyse potential effects for a multitude of failures. By contrast, they emphasised that the FTA is highly effective in determining how robust a design will be to a single failure.

Thus, by consolidating findings from the survey and theory reviewed during the literature review, a framework was proposed to reduce unclear technical requirements, continuous review of requirements and the use of inefficient quality methods that result in projects delays and the use of unplanned resources. The next section discusses the development of a functional framework to solve the current issues within defence technology R & D project execution.

5.5 Development of the Quality Toolbox Framework

This section discusses the design principles followed in developing an effective quality tool framework referred to as the Toolbox framework to optimise defence technology project execution. The layout of the quality methods within the functional framework program is presented and illustrated.

The third study objective of this research was to develop a framework with tailored quality tools based on literature and survey results which the project team can adopt during the execution of defence technology R & D projects. This section proposes a Microsoft Excel® framework with quality tools that will allow the technology R & D project team to select the appropriate methods to enhance the definition, design and testing aspects of defence technology R & D project execution.

According to Van Haren Publishing (2013), a framework is a structure or system for the realisation of a defined result or goal. Wordpress (2016) commented that embedded within the framework are methods that provide an approach to achieve a specific goal. Each methodology as defined by Wordpress (2016) comprises a set of the defined processes to ensure efficient implementation to achieve the specific goal. Van Haren Publishing (2013) admitted that frameworks provide the users with flexibility regarding the partial or entire use of the framework and the methods contained therein. Hence, a framework fits the requirement for a flexible quality toolbox containing methods to optimise the lower level scientific and engineering activities of defence technology project execution.

R & D projects require a systematic method to identify and visualise the flow of information rather than material (Smailagic and Smailagic, 2014). Therefore, the proposed quality tools framework to optimise defence technology R & D project execution employed the information function activity process.

It was discovered during the literature review that there exists a mutual connection amongst quality methods as illustrated in Figure 2.12. Hence, such a connection should be exploited that will ensure a powerful application to optimise defence technology R & D project execution is developed. Consequently, a functional framework was developed with these quality tools to allow the technology R & D project team to select the appropriate tools to enhance the requirements, design and testing aspects of the defence technology R & D project execution. To maintain costs, the framework was developed on the Microsoft Excel® platform because most users are familiar with the software and secondly, most computers have this program installed by default on their computers. As this framework is based on a practical approach, a compact disc (CD) is attached to this dissertation that contains the application (Refer to Annexure I).

At the crux of the quality toolbox framework program is the “Toolbox Menu” within the framework as shown in Figure 5.2. The framework follows a flow of information from left to right and bottom to top. The “Toolbox Menu” comprises of the following headings from left to right which are “Define Requirements”, “Design Concept” and “Evaluate Concept”. These headings are aligned with the current defence technology R & D activities of basic and applied scientific research, testing and experimental development of new weapons and weapon systems (Jha, 2009). Moreover, the "Toolbox Menu" comprises of the following headings from bottom to top:

- **Objectives**: This explains the aim of each method during technology R & D project execution.
- **Responsibility**: Project team required for a specific method.
- **Method**: Methods are the tools implemented during execution. These methods are used to bring about the intended technology R & D project changes or results.
- **Output**: The resulting output of each methods being applied.
- **Outcome**: Final overarching result to the design concept.

From the review of literature in Section 2.2 it was gleaned that quality methods for R & D projects like defence technology R & D projects should be conducted systematically, logically laid out, simple and efficient to use, low cost, not burdensome in terms of more paperwork and embrace the flexible method of defence technology R & D project execution. The main heading in the "Toolbox Menu" is the "Method" section (Shaded area in Figure 5.2) which comprises of the quality tools that follow this approach is detailed in Section 2.2. The methods were categorised into three areas:

- Primary Methods,
- Supplementary Methods, and
- Information Tools.

Several methods were identified in Section 2.3 as the core methods that have enormous potential to optimise defence technology R & D projects due to their ability to reduce dependence on inefficient methods such as Trade Off analysis, Trial and Error, large sample testing and multiple comparative testing and post deliverable quality inspections. The following were identified as primary quality methods:

a. **Quality Function Deployment (QFD)**: Translates functional requirements into technical or design requirements clearly (Alwerfalli and Lash, 2012).
b. **Axiomatic Design**: Is a design Tool for analysing the quality of existing designs and new concepts through thorough analysis of the customers' functional requirements without the use of Trade Off Analysis or Trial and Error Methods (Yang and El Haik, 2003; Banciu and Draghici, 2003).

c. **TRIZ Inventive Problem Solving**: Is a method that provides techniques to help R & D project teams create new designs and avoid numerous Trial and Errors during the problem solving process (Ilevbare et al. 2011; Yang and El Haik, 2003).
d. **Design for Failure Mode Effect Analysis (DFMEA)**: Is a method for evaluating a design for robustness against potential failures (Bottom Up Method) (Cudney and Furterer, 2012).
e. **Fault Tree Analysis (FTA)**: Is a logical, graphical diagram that lays the possible faults within the design concept that may lead to the top-level unwanted fault /failure (Top Down Method) (Teixeira and Soares, 2011; Marshall, 2012).
f. **Pugh Design selection**: Provides a simple approach that evaluates multiple factors on each design when reaching a decision of selecting the best design. (Alwerfalli and Lash, 2012; Lugo, 2012).
g. **Taguchi Robust Design Method:** Is a fractional design of experiment method in solving problems and optimising products and process design. This method was designed to reduce the experimental time and cost and its simplicity in data collection (Ghani et al. 2013).

To ensure optimum use of the primary methods mentioned above, supplementary methods are also listed in this Toolbox framework. The following supplementary methods are used to support the primary methods during implementation as shown in section 2.3:

a. **Design Review**: is a team activity used to evaluate several design alternatives in order to make a final determination on which concept will be used (Yang and El Haik, 2003).
b. **Brainstorming**: Is a tool to generate creative solutions to solve a problem by bringing the diverse experience of all team members into play which increases the opportunity to find better solutions (Mind Tools Limited, 2009).
c. **Ishikawa Cause and Effect Diagram**: Is a method that illustrates the relationship between an effect (problem) and a set of possible causes that produces the effect in a design (Levine et al. 2001).
d. **Block/ P Diagram**: Is a block diagram used to identify noise factors and its interaction with design parameters, controlled inputs and functional requirements (Raytheon, 2007).

The third category is referred to as Information Tools. These tools contain vital data that guide the technology R & D team to accurately populate activities during the implementation of the methods (Refer to Annexures A to E). These information tools include:

a. **Zig and Zag Process**: Are process used by the Axiomatic Design process to list all functional requirements (FR) and technical requirements/ design parameters (DP) of the design (System Design, 2004).
b. **Corollaries and Theorems**: A coupled design may be simplified by smartly adding extra design parameters to the structure by using Axiomatic Design theorems and corollaries (Banciu and Draghici, 2003).
c. **Functional Framework Analysis**: Is a process used by TRIZ Inventive Problem Solving method to identify the problem more clearly and precisely (Yang and El Haik, 2003).
d. **Contradiction Matrix**: 39 x 39 matrix used by TRIZ Inventive Problem Solving method to identify technical contradictions (Yang and El Haik, 2003).
e. **Inventive Principles**: 40 principles used by TRIZ Inventive Problem Solving method to resolve the contradictions identified in the 39 x 39 matrix (Yang and El Haik, 2003).
f. **Severity Rating**: Subjective measure of how bad or serious the effect of the failure mode is during DFMEA and FTA analysis (Yang and El Haik, 2003).
g. **Orthogonal Array Selector:** The Taguchi method utilises orthogonal arrays (OA) to study a large number of variables with a small number of experiments (Shiu et al (2013).
h. **Fault Tree Example:** Are logic diagrams and format to create a fault tree (Marshall, 2012; CQE Academy, 2016).
i. **Cut Set Example:** Is an example of a cut set as illustrated on fault tree (Marshall, 2012; CQE Academy, 2016).
j. **Cut Set in Boolean Algebra:** Is an example of cut set written in Boolean Algebra (Marshall, 2012; CQE Academy, 2016).
k. **Fault Tree Analysis Rules:** Represent 6 rules to assist in defining the complete Fault Tree from the top failure event to the basic events that result in the top failure to occur (Marshall, 2012; CQE Academy, 2016).

Due to the synergy already identified between the methods, both supplementary methods and information tools are coupled with the primary methods hence showing their valuable relationship amongst each other (refer to the section on Toolbox Menu encircled in red in Figure 5.2). The framework provides a diverse selection of methods which the project team may employ. To view the full functionality of the methods in relation to each other, it is recommended that the application is run on Microsoft© Excel platform (Refer to CD in Annexure I).

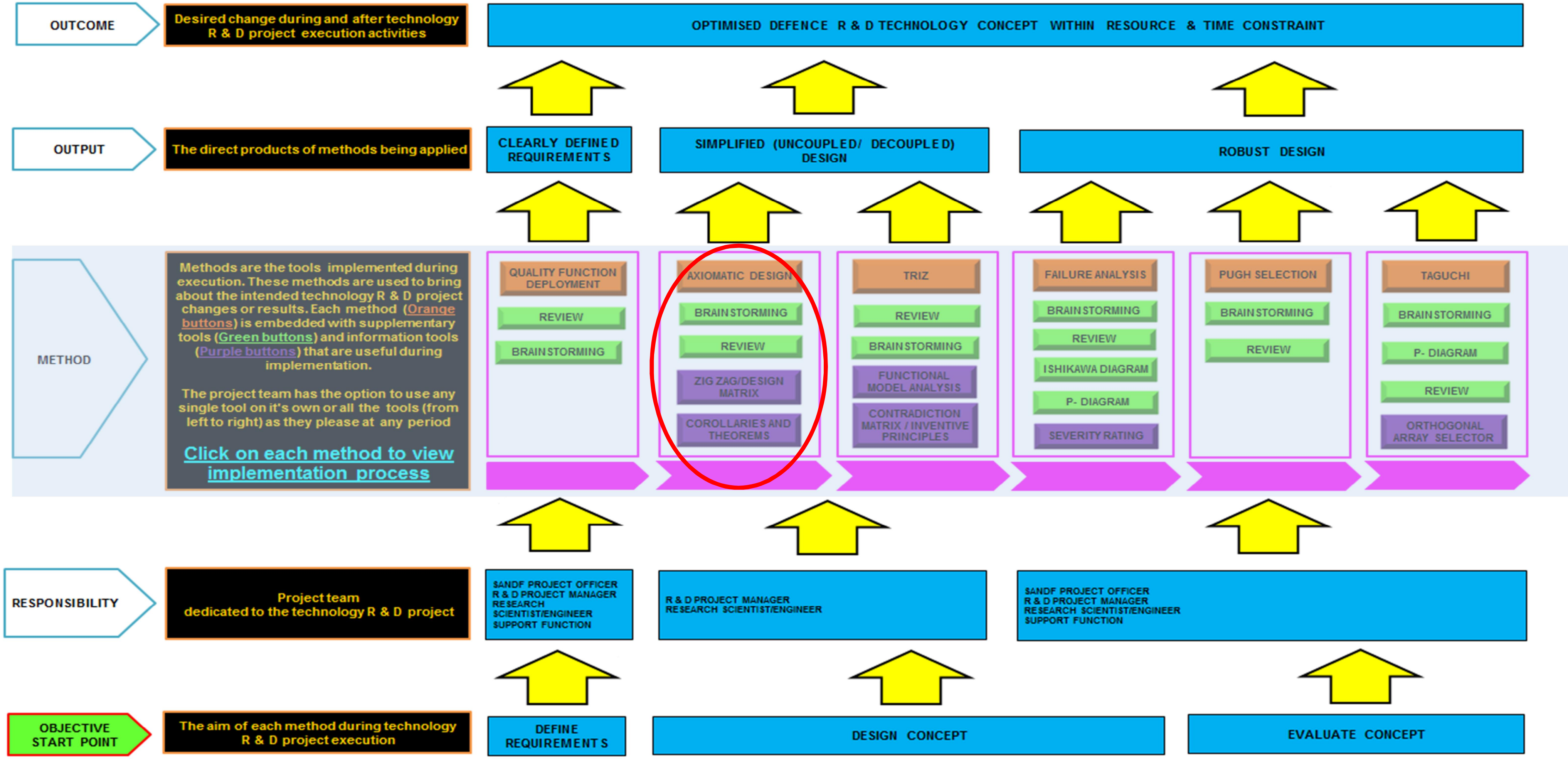


Figure 5.2 Toolbox Menu –Quality Toolbox Framework (Source: Researcher's own construction)

As discussed in Section 2.2, quality methods to optimise defence technology R & D project execution should follow a systematic and logical approach to optimise defence technology R & D activities. Hence the entire framework developed follows this approach. To ensure the Toolbox framework is used to its full potential, Figure 5.3 shows the sequential methodology adopted to explain how the framework functions. The diagram is numbered as follows:

a. **Step 1 Information Sheet**: This is the first sheet that is loaded when the framework is opened on Microsoft© Excel. The information sheet provides background information on why a Toolbox framework was developed.

b. **Step 2 Instruction Sheet**: This sheet provides detailed instructions and illustrations to the user on how to effectively implement the Toolbox framework during defence technology R & D project execution.

c. **Step 3 Toolbox Menu Diagram**: This sheet is the crux of the entire Toolbox framework and is shown in detail in Figure 5.3.

d. **Step 4 Primary Quality Method Flow Chart**: Smailagic and Smailagic (2014) added that activities in R & D projects require a systematic method to identify and visualise the flow of information. Thus, functional frameworks contain processes that explain how to apply methods. Hence, process flow charts or diagrams are used to explain how to use all the primary methods in the framework. Mahdi (2013) stated that a flow chart is a diagram which visually presents the flow of information through a method. Mock (2018) outlined that a flow chart describes an operation sequentially in order to solve a problem. Mahdi (2013) listed advantages of using flow charts which include:
   - Ø A Flowchart can be used as an effective way of communicating the logic of a method and the steps involved in determining the solution.
   - Ø By using flowcharts, it makes updates to the methods in the program easier.

   Mock (2018) also confirmed that flow charts are flexible tools that allow changes to processes to be made in real-time. Therefore, a flow chart is deemed as the best instrument in detailing the processes of the quality tools in the framework to solve design problems. Secondly, it allows updates to the methods to be done quickly. Figure 5.4 provides an example of the setup of flow charts to implement a quality method.

e. **Step 5 Primary Method Matrix Tools**: Several methods such as QFD, DFMEA, Pugh Design Selection and Taguchi are linked to matrices which allows the technology R & D project team to populate data immediately so that it can be analysed. The Toolbox framework is practical and interactive rather than abstract or conceptual which allows the team to apply the various methods by populating the relevant matrix with information. The matrix visually presents the keyed-in data to the team in a structured manner. The Taguchi fractional design of experiment matrix includes equations that quickly calculate the number of experiments to be conducted as well as the final result. Thus, considerable thought had gone into the design of the framework by linking flow chart processes to matrix tools that are aimed at reducing valuable time during implementation.

f. **Step 6 Supplementary Method Flow Chart**: As in the case with the primary methods, the supplementary methods make use of flow charts to explain its processes.

g. **Step 7 Supplementary Method Matrix Tools**: Several supplementary methods such as Ishikawa and P Diagrams are linked to matrices which allow data to be populated and analysed quickly by the project team. As in the case with the primary method matrices, the team populates the relevant matrix in an organised manner with data for quick analysis.

h. **Step 8 Information Tool Sheet:** This collection of sheets include vital information and data on Zig Zag process, Theorems, Corollaries, Functional Framework Analysis, Contradiction matrix, Inventive Principles, Severity Ratings, Orthogonal Array Selections, Fault Tree Rules and Creation. This information can be quickly accessed by the project team using navigation buttons.

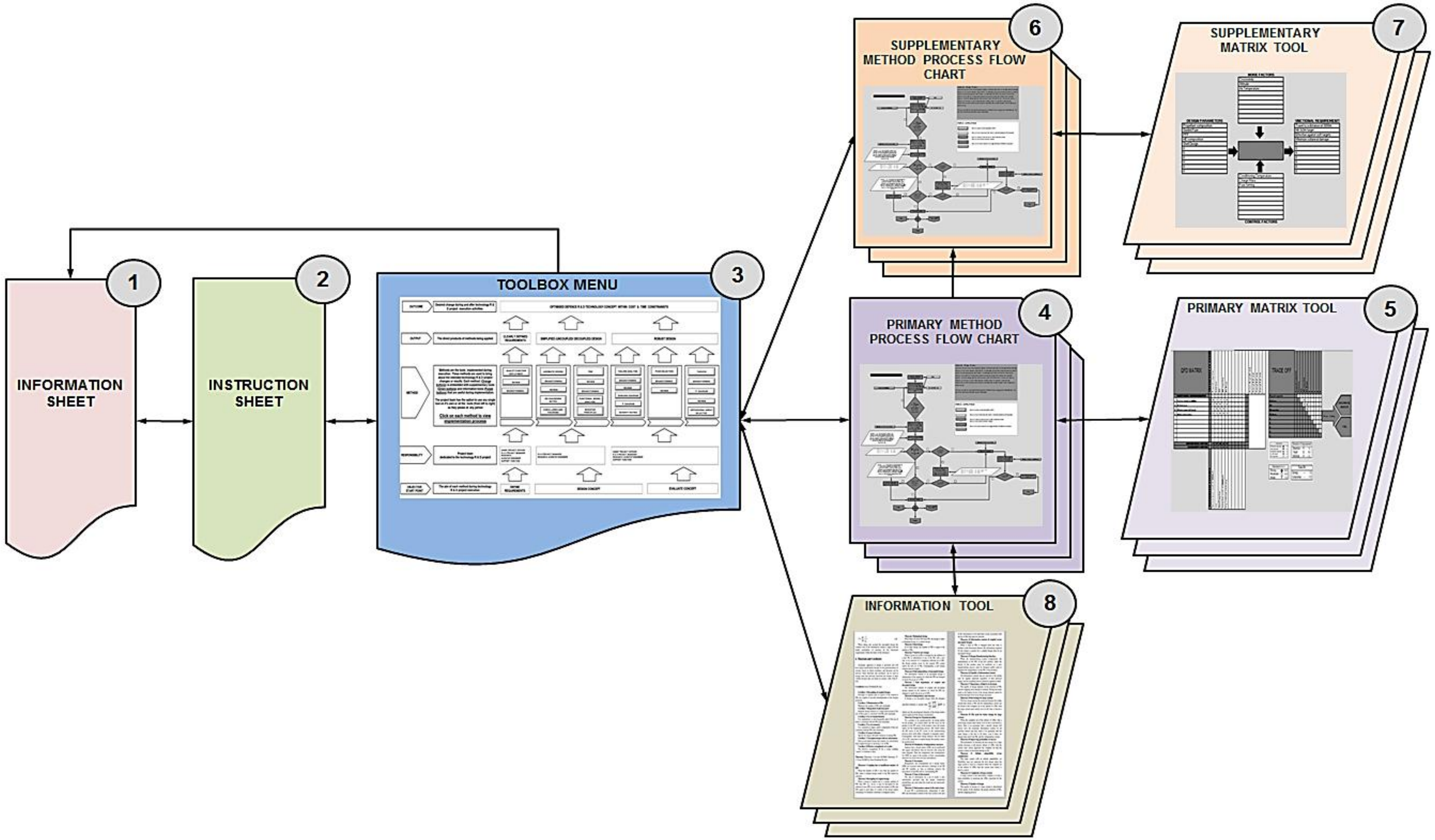


Figure 5.3 Sequential Flow of the Quality Toolbox Framework (Source: Researcher's own construction)

All the methods and tools (Steps 4, 6 and 8 in Figure 5.3) in the Toolbox can be quickly accessed using navigations buttons. Similarly, navigation buttons to exit a specific method and return to the Toolbox Menu have been included. Figure 5.4 illustrates the typical functions of the Toolbox framework during application. In a bid to be time efficient, embedded throughout the framework are colour coded navigation buttons. The functions of these buttons are explained in Figure 5.4 which allows the user to rapidly:

- access quality method processes,
- access matrix tools,
- access supplementary methods,
- information tools,
- exit to main Toolbox Menu, and
- exit to next method.

Thus, the majority of the methods selected for this framework are tools that proactively analyse design concepts during the early stages of the defence technology R & D phase when the design is still on paper. Hence, by comprehensively analysing the design on paper as well as on matrix tools ensures shorter development cycles and the avoidance of redesign during the execution of defence technology R & D projects. Moreover, literature proved that practice of these methods will ensure design concepts are optimised as well as reduce project delays and use of additional resources (Banciu and Draghici, 2003; Yang and El Haik, 2003, Alwerfalli and Lash, 2012; Cudney and Furterer, 2012; Ghani et al. 2013). Figure 2.12 revealed some mutual connection amongst the various quality methods reviewed in Chapter 2. Essentially, the example shown in Figure 5.4 demonstrates the typical value added connections between the various methods. The layout of the entire Toolbox framework presents a defined set of processes which encourage the technology R & D project teams to be focussed, methodical and thorough when evaluating and optimising the quality of design concepts thus ensuring the best outcome is achieved for the SANDF customer.

The developed Toolbox framework was tested during a perception study. Feedback on the framework, conclusion and recommendations of the study are discussed in the next section.

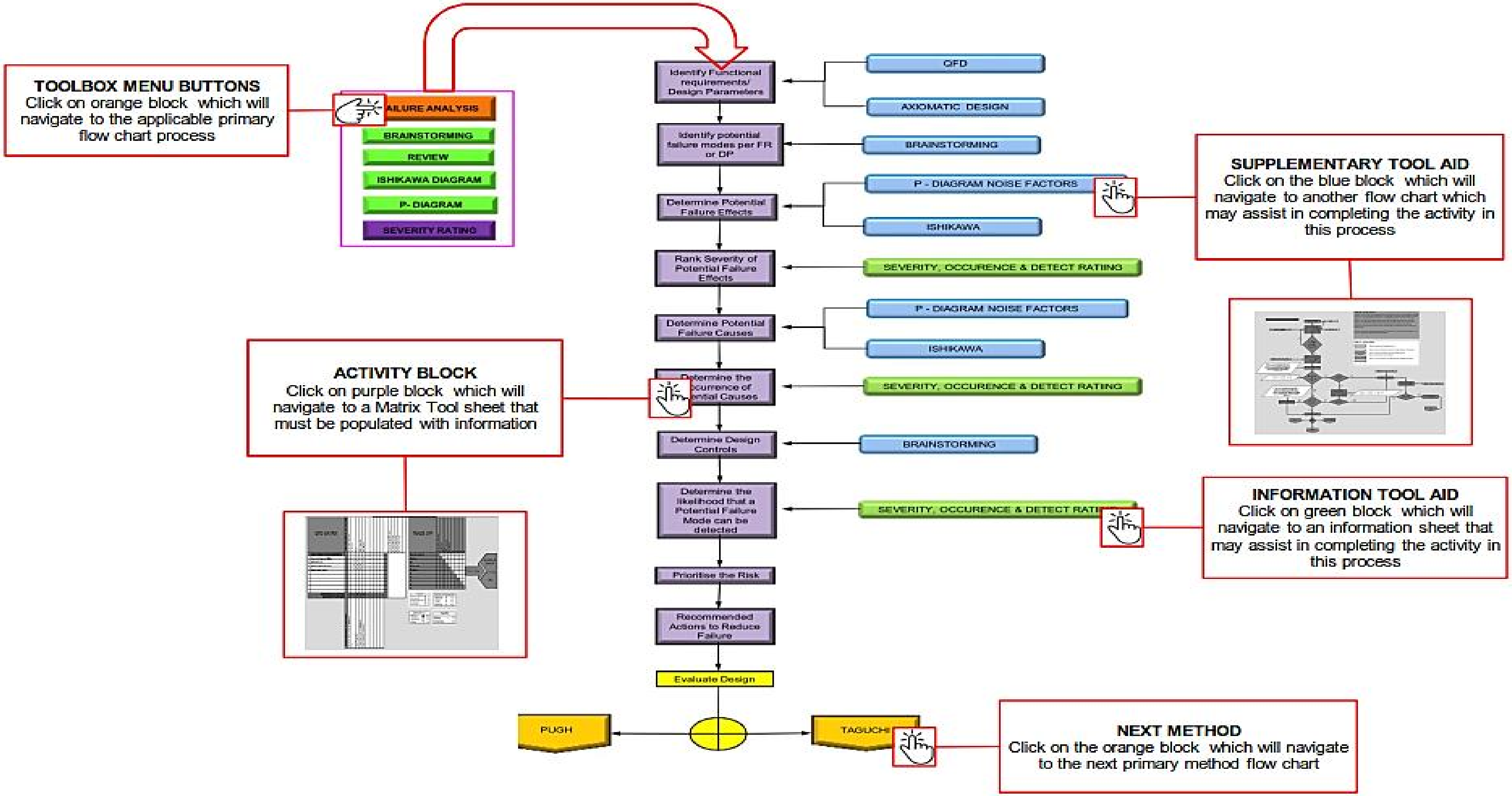


Figure 5.4 Example of How the Quality Toolbox Framework Function (Source: Researcher's own construction)

5.6 Conclusion and Recommendations

This section presented the final aspects of this research study where results from the perception study are revealed, subsequent recommendations and future research are suggested, culminating in the review of the study objectives and a final comment by the researcher on the investigation that was undertaken.

5.6.1 Results from Perception Study on Framework

The fourth and final study objective was to conduct a perception study of the framework developed to determine its suitability for defence technology R & D project execution application. Consequently, a perception study on the framework shown in Section 5.5 was conducted to test the functionality, identify gaps within the content (quality method processes) and obtain recommendations to improve the framework for future application within Defence technology R & D project execution. This survey was critical as it will determine whether the Toolbox framework is useable and acceptable amongst the defence technology R & D project team.

The result of the study was as follows:

a. For Question 1, on whether it was easy to navigate to all the methods in the framework, 100% of the respondents replied “Definitely”.

b. For Question 2, on whether the framework contains adequate information that explains how each method can be implemented,
   - Ø 70% of the respondents replied “Definitely”
   - Ø 30% of the respondents replied “Yes, with improvements”

   Respondents who replied “Yes, with improvements” listed guidance documents and training manuals would be useful, particularly for inexperienced users.

c. For Question 3, on whether there are similar low cost functional frameworks available to optimise Defence technology R & D projects that encompass these quality tools into a single program,
   - Ø 40% of the respondents replied “Not Sure”
   - Ø 60% of the respondents replied “No” there are no similar frameworks.

d. For Question 4, on whether the user would be prepared to use this framework during the execution of their defence technology R & D projects, 80% of the respondents replied “Definitely”.

e. For Question 5, on whether the user would require additional training to understand how to effectively implement the quality tools in this framework,

- Ø 30% of the respondents replied “Definitely not”
- Ø 70% of the respondents replied “Yes, I would require training”

Respondents who replied “Yes, I would require training” listed Axiomatic design, TRIZ, Pugh Selection, FTA and Taguchi Robust Design methods.

f. For Question 6, on whether the quality tools in this framework will aid in optimising defence technology project execution by reducing project delays and use of unplanned resources, 100% of the respondents replied “Definitely”.

g. For Question 7, on what differentiates this framework from other frameworks, the respondents listed the following unique strengths of the framework as shown in Figure 5.5

- Ø The ability of the framework to be flexible proved to be a defining characteristic (Ability 2 at 47%).
- Ø Design and layout of the framework was also a strength that the respondents observed (Ability 1 at 21%).
- Ø In addition, the practical approach of the framework was another characteristic that impressed the respondents (Ability 3 at 26%).
- Ø Finally, another ability that was identified is the framework being comprehensive in terms of its content. (Ability 4).

Ability 1	Design such as use of navigation buttons, flow diagrams, matrices, information blocks to explain and illustrate the methods
Ability 2	Ability to be flexible where one method OR a combination of methods OR all methods can be applied to optimise defence technology R & D project execution
Ability 3	Practical approach rather than theoretical or abstract were the methods in the Framework can be implemented
Ability 4	Other abilities

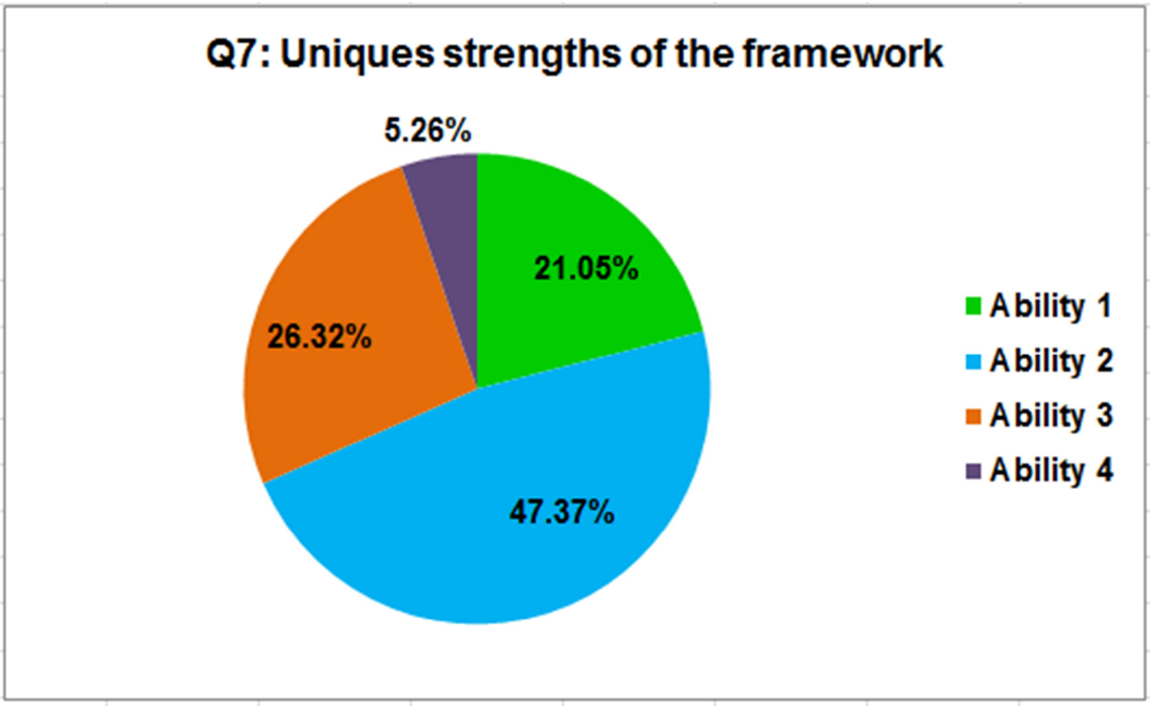


Figure 5.5 Question 7 Unique strengths of the Toolbox Framework (Source: Researcher's own construction)

h. For Question 8, on whether the framework provides a sound basis onto which other quality methods identified in future can be built into, 100% of the respondents replied "Definitely".

i. For the optional Question 9, respondents freely listed other improvements to the framework that would guarantee a more effective Toolbox during implementation. This included the use of examples to explain how each method functions.

On first glimpse of the Toolbox framework, the respondents were impressed with the layout and content of the framework. The respondents highlighted several unique traits of the framework which included its flexible methods and practical approach in optimising defence technology R& D project execution. The initial design of the framework has shown potential and with several adjustments could prove to be a highly effective tool in optimising defence technology R & D project execution. As highlighted in earlier discussions, a framework with quality methods for technology R & D project execution has been absent in the environment. Hence, it is not surprising that the respondents have acknowledged the need for such a framework. The next section will discuss the recommendations to optimise the Toolbox framework and will take into consideration the suggestions of respondents during the perception study.

5.6.2 Recommendations and Future Research

To ensure successful implementation of the quality toolbox framework developed for the defence technology R & D project execution, the following recommendations are listed:

a. **Detailed instruction or manual:** As the framework becomes larger and more comprehensive in the future with the inclusion of the new quality methods or even updates to existing methods, there may arise a need to draft a detailed procedure to use all methods. Further, it was also recommended by respondents during the perception that a comprehensive manual be compiled to assist inexperienced users. Feedback from the perception study also suggested the use of examples and scenarios to explain how a method works should be included.

b. **Workshops and awareness training**: It was noted during the perception study that several of the methods may require training. Hence, training sessions to educate the defence technology R & D project teams on these methods should be scheduled. Rather than a formal lecture, the training should be interactive where the students should be doing practical exercises by using the framework program on their computers. Training or workshops should be scheduled periodically to train new employees, as well as serve as a refresher course for existing employees. Moreover, the manual or instructions developed for the framework should be used as a source document to train the delegates.

c. **Exploit electronic mediums**: The framework is set up to be uploaded immediately onto an organisation's intranet. Thus, this network would serve as a great opportunity for employees to quickly access the framework. Furthermore, the intranet could serve as a great platform to receive feedback where suggestions, compliments and even criticisms on the framework should be acknowledged. This continual feedback would provide the catalyst to continually enhance the framework. Another potential that the framework possesses is the ability for the instrument to be converted into an application tool. According to Mahdi (2013), flow charts allow easy coding of the program into the latest computer software programs. Hence as this functional framework is built on flow charts, it would be ideal to translate this tool into an app that can be accessed on any computer platform or electronic device (mobile phones and tablets) no matter the operating system.

d. **Enhance application:** Streamlining the number of activities within each method by combing specific activities into one function should be investigated in the next revision of the framework. As recommended during the perception study the inclusion of additional hyperlink buttons for quick access directly to other methods should be explored.

e. **Expand the application to other fields**: As emphasised in Chapter 2, the quality tools that were reviewed, predominately originated from the commercial and civil technology R & D project environment. Though the framework was created to curb inefficiencies within the defence technology R & D project execution environment, an opportunity does exist to use this framework in other non-defence technology R & D environments.

As processes to define, design and test defence technologies continue to evolve, new quality methods will have to be developed or updated in order to keep up with this technological advancement trend. Future research on these novel methods should be conducted to ascertain its relevance and possible inclusion to the Toolbox functional framework. It was also identified during the survey that other challenges within the defence industry in general do exist such as poor maintenance of equipment, obsolescence of military equipment, lack of transformation in the defence industry, project management challenges, change management issues, lack of focus and synergy within SANDF, lack of expertise in defence technology R & D projects and complicated defence acquisition processes. Each of these areas of concern could be investigated in detail in the future.

5.6.3 Conclusion to Chapter 5

The aim of this research was to identify suitable quality tools to optimise defence technology R & D project execution with the intention to develop efficient military solutions in the areas of firepower, protection, mobility, sustainability and reconnaissance for the SANDF within time, budget and performance constraints. In summary, the research study investigated the following:

a. **To identify, using a survey, challenges experienced by project teams that are generating redesign activities culminating in project delays and use of unplanned resources during the execution of defence technology R & D projects**: The result of survey indicated a common trend amongst technology R & D project teams that continual technical requirements changes, the practice of inefficient quality methods plus the lack of suitable quality methods designed for Technology R & D projects result in continual project delays and the use of unplanned resources. Inferential statistical analysis of the survey results confirmed and quantified the influence of these inefficient methods on project delays and the use of unplanned resources.

b. **To identify from a survey, suitable quality tools that are applied during the research (definition) and development (design and testing) phase to optimise the execution of defence technology R & D projects**: Respondents were provided with an opportunity to list suitable quality tools for defence technology R & D project execution. The results of the survey revealed a deficiency in the use of suitable quality tools for technology R & D projects execution. Instead, respondents still advocated the practise of inefficient methods as revealed in Section 4.3.

c. **To develop a framework with tailored quality tools based on literature and survey results which the project team can adopt during the execution of defence technology R & D projects**: The development of a functional framework was discussed in Section 5.5. The framework's layout, application and inclusion of various quality tools to assist the technology R & D project teams in clearly defining requirements, reducing complexity in designs and evaluating design concepts for robustness was detailed. The design of the framework was in a Toolbox format which aimed to follow the approach recommended in literature that the selected methods should be flexible, systematic, logical, simple and efficient to use, low cost and not burdensome in terms of more paperwork.

d. **To conduct a perception study of the framework developed with quality tools to determine suitability for defence technology R & D project execution application**. The perception study revealed productive feedback on the framework as detailed in Section 5.6.1. Apart from minor recommendations suggested by the respondents, the overall impression on the design, layout and content of the Toolbox functional framework was positive. The results of the perception study confirmed that the methods selected for the framework are suitable to optimise defence technology project execution. In its current configuration, the framework may be implemented during defence technology project execution.

Thus, it can be noted that challenges experienced within defence technology R & D projects due to chronic project delays and the use of unplanned resources can be reduced or removed with innovative quality tools which were identified from literature. The consolidation of these methods into a solid functional framework should prevent the project team's reliance on improper methods to optimise defence technology project execution. Initial feedback on the framework showed that respondents are willing to implement the program. With further enhancements and continual updates, it is hoped that the framework reduces inefficiencies, as well as ensure that superior military technologies are continually developed for the SANDF. The aims and objectives as described in Section 1.3 have hence been achieved completely. As this research focused on the technical quality issues within the defence technology R & D projects, future research should be expanded to investigate other areas of concern such as political, strategic and management within the South African defence industry.

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ANNEXURE A: AXIOMATIC DESIGN THEOREMS AND COLLARIES (Source: Banciu and Draghici, 2003)

$$I = \sum_{i=1}^{n} \frac{1}{A_{cri}} \qquad (10)$$

When taking into account the uncoupled design the smallest sum of the information content is equal with the higher probability of meeting all the functional requirements within the limits of the tolerances

6. Theorems and Corollaries

Axiomatic approach to design is powerful and will have many ramifications because of the generalizability of axioms, based on which corollaries and theorems can be derived. These theorems and corollaries can be used as design rules that precisely prescribe the bounds of their validity because they are based on axioms. (Suh, Nam P., [8])

Corollaries from (Nordlund M.,[6]) :

Corollary 1 Decoupling of coupled designs

Decouple or separate parts or aspects of the solution if FRs are coupled or become interdependent in the designs proposed.

Corollary 2 Minimization of FRs

Minimize the number of FRs and constraints.

Corollary 3 Integration of physical parts

Integrate design features in a single physical part if the use of these parts is consistent with FRs and constraints.

Corollary 4 Use of standardization

Use standardized or interchangeable parts if the use of these is consistent with the FRs and constraints.

Corollary 5 Use of symmetry

Use symmetrical shapes and/or components if they are consistent with the FRs and constraints.

Corollary 6 Largest tolerance

Specify the largest allowable tolerance in stating FRs.

Corollary 7 Uncoupled design with less information

Seek an uncoupled design that requires less information than coupled designs in satisfying a set of FRs.

Corollary 8 Effective reangularity of a scalar

The effective reangularity R for a scalar coupling "matrix" or element is unity.

Theorems (Theorems 1-16 from [SUH90] Theorems 17-23 from [SUH95c]) from (Nordlund M.,[6]):

Theorem 1 Coupling due to insufficient number of DPs

When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.

Theorem 2 Decoupling of coupled design

When a design is coupled due to a greater number of FRs than DPs (i.e., m.>n), it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other, if a subset of the design matrix containing n*n elements constitutes a triangular matrix.

Theorem 3 Redundant design

When there are more DPs than FRs, the design is either a redundant design or a coupled design.

Theorem 4 Ideal design

In an ideal design, the number of DPs is equal to the number of FRs.

Theorem 5 Need for new design

When a given set of FRs is changed by the addition of a new FR, or substitution of one of the FRs with a new one, or by selection of a completely different set of FRs, the design solution given by the original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.

Theorem 6 Path independence of uncoupled design

The information content of an uncoupled design is independent of the sequence by which the DPs are changed to satisfy the given set of FRs.

Theorem 7 Path dependency of coupled and decoupled design

The information contents of coupled and decoupled designs depend on the sequence by which the DPs are changed to satisfy the given set of DPs.

Theorem 8 Independence and tolerance

A design is an uncoupled design when the designer specified tolerance is greater than $\sum_{\substack{j\neq 1\\ i=1}}^{n} \left(\frac{\partial FR_i}{\partial DP_j} \right) \Delta DP_j$ in which case the non-diagonal elements of the design matrix can be neglected from design consideration.

Theorem 9 Design for Manufacturability

For a product to be manufacturable, the design matrix for the product, [A] (which relates the FR vector for the product to the DP vector of the product) times the design matrix for the manufacturing process, [B] (which relates the DP vector to the PV vector of the manufacturing process) must yield either a diagonal or triangular matrix. Consequently, when these design matrices; that are either [A] or [B], represents a coupled design, the product cannot be manufactured.

Theorem 10 Modularity of independence measures

Suppose that a design matrix [DM] can be partitioned into square sub-matrices that are non-zero only along the main diagonal. Then the reangularity and semangularity for [DM] are equal to the product of their corresponding measures for each of the non-zero sub-matrices.

Theorem 11 Invariance

Reangularity and semangularity for a design matrix [DM] are invariant under alternative orderings of the FR and DP variables, as long as orderings preserve the association of each FR with its corresponding DP.

Theorem 12 Sum of information

The sum of information for a set of events is also information, provided that the proper conditional probabilities are used when the events are not statistically independent.

Theorem 13 Information content of the total system

If each DP is probabilistically independent of other DPs, the information content of the total system is the sum of the information of all individual events associated with the set of FRs that must be satisfied.

Theorem 14 Information content of coupled versus uncoupled designs

When a state of FRs is changed from one state to another in the functional domain, the information required for the change is greater for a coupled design than for an uncoupled design.

Theorem 15 Design-Manufacturing Interface

When the manufacturing system compromises the independence of the FRs of the new product, either the design of the product must be modified, or a new manufacturing process must be designed and/or used to maintain the independence of the FRs of the products.

Theorem 16 Equality of information content

All information contents that are relevant to the design task are equally important regardless of their physical origin, and no weighting factors should be applied to them.

Theorem 17 Importance of high level decisions

The quality of design depends on the selection of FRs and the mapping from domain to domain. Wrong decisions made at the highest levels of the design domain cannot be rectified through lower level design decisions

Theorem 18 Best design for large systems

The best design among the proposed designs for a large system that satisfy n FRs and the independence axiom can be chosen if the complete set of the subsets of {FRs} that the large system must satisfy over its life time is known a priori.

Theorem 19 The need for better design for large systems

When the complete set of the subsets of {FRs} that a given large system must satisfy over its life is not known a priori, there is no guarantee that a specific design will always have the minimum information content for all possible subsets and thus, there is no guarantee that the same design is the best at all times, even if there are designs that satisfy the FRs and the independence axiom.

Theorem 20 Improving probability of success

The probability of choosing the best design for a large system increases as the known subsets of {FRs} that the system must satisfy approach the complete set that the system is likely to encounter during its life.

Theorem 21 Infinite adaptability versus completeness

The large system with an infinite adaptability (or flexibility) may not represent the best design when the large system is used in a situation where the complete set of the subsets of {FRs} that the system must satisfy is known a priori.

Theorem 22 Complexity of large systems

A large system is not necessarily complex if it has a high probability of satisfying the {FRs} specified for the system.

Theorem 23 Quality of design

The quality of design of a large system is determined by the quality of the database, the proper selection of FRs, and the mapping process.

ANNEXURE B: TECHNICAL CONTRADICTION MATRIX (Source: Altshuller, 2007)

Worsening Feature →

No.	Improving Feature	1 Weight of moving object	2 Weight of stationary object	3 Length of moving object	4 Length of stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force (Intensity)	11 Stress or pressure	12 Shape	13 Stability of the object's composition	14 Strength	15 Duration of action of moving object	16 Duration of action of stationary object	17 Temperature	18 Illumination intensity	19 Use of energy by moving object	20 Use of energy by stationary object
1	Weight of moving object	+		15,8, 29,34		29,17, 38,34		29,2, 40,28		2,8, 15,38	8,10, 18,37	10,36, 37,40	10,14, 35,40	1,35, 19,39	28, 27,18,	5,34, 31,35		6,29, 4,38	19,1, 32	35,12, 34,31	
2	Weight of stationary object		+		10,1, 29,35		35, 30,13,		5,35, 14,2		8,10, 19,35	13,29, 10,18	13,10, 29,14	26, 39,1,	28,2, 10,27		2,27, 19,6	28,19, 32,22	19,32, 35		18,19, 28,1
3	Length of moving object	8,15, 29,34		+		15,17, 4		7,17, 4,35		13,4, 8	17,10, 4	1,8, 35	1,8, 10,29	1,8, 15,34	8,35, 29,34	19		10,15, 19	32	8,35, 24	
4	Length of stationary object		35, 28,		+		17,7, 10,40		35,8, 2,14		28,10	1,14, 35	13,14, 15,7	39, 37,35	15,14, 28,26		1,10, 35	3,35, 38,18	3,25		
5	Area of moving object	2,17, 29,4		14,15, 18,4		+		7,14, 17,4		29, 30,4,	19,30, 35,2	10,15, 36,28	5,34, 29,4	11,2, 13,39	3,15, 40,14	6,3		2,15, 16	15,32, 19,13	19,32	
6	Area of stationary object		30,2, 14,18		26,7, 9,39		+				1,18, 35,36	10,15, 36,37		2,38	40		2,10, 19,30	35, 39,38			
7	Volume of moving object	2,26, 29,40		1,7,4, 35		1,7,4, 17		+		29,4, 38,34	15,35, 36,37	6,35, 36,37	1,15, 29,4	28,10, 1,39	9,14, 15,7	6,35, 4		34, 39,10,	2,13, 10	35	
8	Volume of stationary object		35,10, 19,14	19,14	35,8, 2,14				+		2,18, 37	24,35	7,2, 35	34, 28,	9,14, 17,15		35, 34,38	35,6, 4			
9	Speed	2,28, 13,38		13,14, 8		29, 30,34		7,29, 34		+	13,28, 15,19	6,18, 38,40	35,15, 18,34	28, 33,1,	8,3, 26,14	3,19, 35,5		28, 30,	10,13, 19	8,15, 35,38	
10	Force (Intensity)	8,1, 37,18	18,13, 1,28	17,19, 9,36	28,10	19,10, 15	1,18, 36,37	15,9, 12,37	2,36, 18,37	13,28, 15,12	+	18,21, 11	10,35, 40,34	35,10, 21	35,10, 14,27	19,2		35,10, 21		19,17, 10	1,16, 36,37
11	Stress or pressure	10,36, 37,40	13,29, 10,18	35,10, 36	35,1, 14,16	10,15, 36,28	10,15, 36,37	6,35, 10	35,24	6,35, 36	36, 35,21	+	35,4, 15,10	35, 33,2,	9,18, 3,40	19,3, 27		35, 39,19,		14,24, 10,37	
12	Shape	8,10, 29,40	15,10, 26,3	29, 34,5,	13,14, 10,7	5,34, 4,10		14,4, 15,22	7,2, 35	35,15, 34,18	35,10, 37,40	34,15, 10,14	+	33,1, 18,4	30,14, 10,40	14,26, 9,25		22,14, 19,32	13,15, 32	2,6, 34,14	
13	Stability of the object's composition	21,35, 2,39	26, 39,1,	13,15, 1,28	37	2,11, 13	39	28,10, 19,39	34, 28,	33,15, 28,18	10,35, 21,16	2,35, 40	22,1, 18,4	+	17,9, 15	13,27, 10,35	39,3, 35,23	35,1, 32	32,3, 27,16	13,19	27,4, 29,18
14	Strength	1,8, 40,15	40, 26,	1,15, 8,35	15,14, 28,26	3,34, 40,29	9,40, 28	10,15, 14,7	9,14, 17,15	8,13, 26,14	10,18, 3,14	10,3, 18,40	10,30, 35,40	13,17, 35	+	27,3, 26		30,10, 40	35,19	19,35, 10	35
15	Duration of action of moving object	19,5, 34,31		2,19, 9		3,17, 19		10,2, 19,30		3,35, 5	19,2, 16	19,3, 27	14,26, 28,25	13,3, 35	27,3, 10	+		19,35, 39	2,19, 4,35	28,6, 35,18	
16	Duration of action by stationary object		6,27, 19,16		1,40, 35				35, 34,38					39,3, 35,23			+	19,18, 36,40			
17	Temperature	36,22, 6,38	22, 35,32	15,19, 9	15,19, 9	3,35, 39,18	35,38	34, 39,	35,6, 4	2,28, 36,30	35,10, 3,21	35, 39,19,	14,22, 19,32	1,35, 32	10,30, 22,40	19,13, 39	19,18, 36,40	+	32, 30,21,	19,15, 3,17	
18	Illumination intensity	19,1, 32	2,35, 32	19,32, 16		19,32, 26		2,13, 10		10,13, 19	26,19, 6		32,30	32,3, 27	35,19	2,19, 6		32, 35,19	+	32,1, 19	32, 35,1,
19	Use of energy by moving object	12,18, 28,31		12,28		15,19, 25		35,13, 18		8,35, 35	16,26, 21,2	23,14, 25	12,2, 29	19,13, 17,24	5,19, 9,35	28, 35,6,	-	19,24, 3,14	2,15, 19	+	-

No.	Improving Feature	21 Power	22 Loss of Energy	23 Loss of Substance	24 Loss of Information	25 Loss of Time	26 Quantity of substance	27 Reliability	28 Measurement accuracy	29 Manufacturing precision	30 Object-affected harmful factors	31 Object-generated harmful factors	32 Ease of manufacture	33 Ease of operation	34 Ease of repair	35 Adaptability or versatility	36 Device complexity	37 Difficulty of detecting and measuring	38 Extent of automation	39 Productivity
1	Weight of moving object	12,36, 18,31	6,2, 34,19	5,35, 3,31	10,24, 35	10,35, 20,28	3,26, 18,31	1,3, 11,27	28, 27,	28, 35,	22,21, 18,27	22, 35,31,	27, 28,1,	35,3, 2,24	2,27, 28,11	29,5, 15,8	26, 30,	28, 29,	26,35 18,19	35,3, 24,37
2	Weight of stationary object	15,19, 18,22	18,19, 28,15	5,8, 13,30	10,15, 35	10,20, 35,26	19,6, 18,26	10,28, 8,3	18,26, 28	10,1, 35,17	2,19, 22,37	35, 22,1,	28,1, 9	6,13, 1,32	2,27, 28,11	19,15, 29	1,10, 26,39	25, 28,17,	2,26, 35	1,28, 15,35
3	Length of moving object	1,35	7,2, 35,39	4,29, 23,10	1,24	15,2, 29	29,35	10,14, 29,40	28, 32,4	10,28, 29,37	1,15, 17,24	17,15	1,29, 17	15,29, 35,4	1,28, 10	14,15, 1,16	1,19, 26,24	35,1, 26,24	17,24, 26,16	14,4, 28,29
4	Length of stationary object	12,8	6,28	10,28, 24,35	24, 26,	30, 29,14		15,29, 28	32, 28,3	2,32, 10	1,18		15,17, 27	2,25	3	1,35	1,26	26		30,14, 7,26
5	Area of moving object	19,10, 32,18	15,17, 30,26	10,35, 2,39	30,26	26,4	29, 30,6,	29,9	26, 28,	2,32	22, 33,	17,2, 18,39	13,1, 26,24	15,17, 13,16	15,13, 10,1	15,30	14,1, 13	2,36, 26,18	14,30, 28,23	10,26, 34,2
6	Area of stationary object	17,32	17,7, 30	10,14, 18,39	30,16	10,35, 4,18	2,18, 40,4	32, 35,	26, 28,	2,29, 18,36	27,2, 39,35	22,1, 40	40,16	16,4	16	15,16	1,18, 36	2,35, 30,18	23	10,15, 17,7
7	Volume of moving object	35,6, 13,18	7,15, 13,16	36, 39,	2,22	2,6, 34,10	29, 30,7	14,1, 40,11	25, 26,28	25, 28,2,	22,21, 27,35	17,2, 40,1	29,1, 40	15,13, 30,12	10	15,29	26,1	29, 26,4	35, 34,16,	10,6, 2,34
8	Volume of stationary object	30,6		10,39, 35,34		35,16, 32 18	35,3	2,35, 16		35,10, 25	34, 39,19,	30,18, 35,4	35		1		1,31	2,17, 26		35, 37,10,
9	Speed	19,35, 38,2	14,20, 19,35	10,13, 28,38	13,26		10,19, 29,38	11,35, 27,28	28, 32,1,	10,28, 32,25	1,28, 35,23	2,24, 35,21	35,13, 8,1	32, 28,13,	34,2, 28,27	15,10, 26	10,28, 4,34	3,34, 27,16	10,18	
10	Force (Intensity)	19,35, 18,37	14,15	8,35, 40,5		10,37, 36	14,29, 18,36	3,35, 13,21	35,10, 23,24	28, 29,	1,35, 40,18	13,3, 36,24	15,37, 18,1	1,28, 3,25	15,1, 11	15,17, 18,20	26, 35,10,	36, 37,10,	2,35	3,28, 35,37
11	Stress or pressure	10,35, 14	2,36, 25	10,36, 3,37		37, 36,4	10,14, 36	10,13, 19,35	6,28, 25	3,35	22,2, 37	2,33, 27,18	1,35, 16	11	2	35	19,1, 35	2,36, 37	35,24	10,14, 35,37
12	Shape	4,6,2	14	35, 29,3,		14,10, 34,17	36,22	10,40, 16	28, 32,1	32, 30,40	22,1, 2,35	35,1	1,32, 17,28	32,15, 26	2,13,1	1,15, 29	16,29, 1,28	15,13, 39	15,1, 32	17,26, 34,10
13	Stability of the object's composition	32, 35,	14,2, 39,6	2,14, 30,40		35,27	15,32, 35		13	18	35, 24,	35, 40,	35,19	32, 35,30	2,35, 10,16	35, 30,	2,35, 22,26	35, 22,	1,8, 35	23, 35,
14	Strength	10,26, 35,28	35	35, 28,31,		29,3, 28,10	29,10, 27	11,3	3,27, 16	3,27	18,35, 37,1	15,35, 22,2	11,3, 10,32	32, 40,	27,11, 3	15,3, 32	2,13, 25,28	27,3, 15,40	15	29, 35,10,
15	Duration of action of moving object	19,10, 35,38		28, 27,3,	10	20,10, 28,18	3,35, 10,40	11,2, 13	3	3,27, 16,40	22,15, 33,28	21,39, 16,22	27,1, 4	12,27	29,10, 27	1,35, 13	10,4, 29,15	19,29, 39,35	6,10	35,17, 14,19
16	Duration of action by stationary object	16		27,16, 18,38	10	28, 20,10,	3,35, 31	34, 27,6,	10,26, 24		17,1, 40,33	22	35,10	1	1	2		25, 34,6,	1	20,10, 16,38
17	Temperature	2,14, 17,25	21,17, 35,38	21,36, 29,31		35, 28,21,	3,17, 30,39	19,35, 3,10	32,19, 24	24	22, 33,	22, 35,2,	26,27	26,27	4,10, 16	2,18, 27	2,17, 16	3,27, 35,31	26,2, 19,16	15,28, 35
18	Illumination intensity	32	13,16, 1,6	13,1	1,6	19,1, 26,17	1,19		11,15, 32	3,32	15,19	35,19, 32,39	19,35, 28,26	28, 26,19	15,17, 13,16	15,1, 19	6,32, 13	32,15	2,26, 10	2,25, 16
19	Use of energy by moving object	6,19, 37,18	12,22, 15,24	35, 24,18,		35, 38,19,	34, 23,16,	19,21, 11,27	3,1, 32		1,35, 6,27	2,35, 6	28, 26,30	19,35	1,15, 17,28	15,17, 13,16	2,29, 27,28	35,38	32,2	12,28, 35

20	**Use of energy by stationary object**		19, 9, 6, 27								36, 37			27, 4, 29, 18	35				19, 2, 35, 32	-	+			28, 27, 18,			3, 35, 31	10, 36, 23			10, 2, 22, 37	19, 22, 18	1, 4					19, 35, 16, 25		1, 6
21	**Power**	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37		19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	15, 35, 2	26, 2, 36, 35	22, 10, 35	29, 14, 2, 40	35, 32, 15,	26, 10, 28	19, 35, 10, 38	16	2, 14, 17, 25	16, 6, 19	16, 6, 19, 37		+	10, 35, 38	28, 27, 18,	10, 19	35, 20, 10,	4, 34, 19	19, 24, 26, 31	32, 15, 2	32, 2	19, 22, 31, 2	2, 35, 18	26, 10, 34	26, 35, 10	35, 2, 10, 34	19, 17, 34	20, 19, 30, 34	19, 35, 16	28, 2, 17	28, 35, 34
22	**Loss of Energy**	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	16, 35, 38	36, 38			14, 2, 39, 6	26			19, 38, 7	1, 13, 32, 15			3, 38	+	35, 27, 2,	19, 10	10, 18, 32, 7	7, 18, 25	11, 10, 35	32		21, 22, 35, 2	21, 35, 2, 22		35, 32, 1	2, 19		7, 23	35, 3, 15, 23	2	28, 10, 29, 35
23	**Loss of substance**	35, 6, 23, 40	35, 6, 22, 32	14, 29, 10, 39	10, 28, 24	35, 2, 10, 31	10, 18, 39, 31	1, 29, 30, 36	3, 39, 18, 31	10, 13, 28, 38	14, 15, 18, 40	3, 36, 37, 10	29, 35, 3,	2, 14, 30, 40	35, 28, 31,	28, 27, 3,	27, 16, 18, 38	21, 36, 39, 31	1, 6, 13	35, 18, 24, 5	28, 27, 12,	28, 27, 18,	35, 27, 2,	+		15, 18, 35, 10	6, 3, 10, 24	10, 29, 39, 35	16, 34, 31, 28	35, 10, 24, 31	33, 22,	10, 1, 34, 29	15, 34, 33	32, 28, 2,	2, 35, 34, 27	15, 10, 2	35, 10, 28, 24	35, 18, 10, 13	35, 10, 18	28, 35, 10,
24	**Loss of Information**	10, 24, 35	10, 35, 5	1, 26	26	30, 26	30, 16		2, 22	26, 32						10	10		19			10, 19	19, 10		+	24, 26,	24, 28, 35	10, 28, 23			22, 10, 1	10, 21, 22	32	27, 22				35, 33	35	13, 23, 15
25	**Loss of Time**	10, 20, 37, 35	10, 20, 26, 5	15, 2, 29	30, 24, 14,	26, 4, 5, 16	10, 35, 17, 4	2, 5, 34, 10	35, 16, 32, 18		10, 37, 36, 5	37, 36, 4	4, 10, 34, 17	35, 3, 22, 5	29, 3, 28, 18	20, 10, 28, 18	28, 20, 10,	35, 29, 21,	1, 19, 26, 17	35, 38, 19,	1	35, 20, 10,	10, 5, 18, 32	35, 18, 10, 39	24, 26,	+	35, 38, 18,	10, 30, 4	24, 34,	24, 26,	35, 18, 34	35, 22, 18,	35, 28,	4, 28, 10, 34	32, 1, 10	35, 28	6, 29	18, 28, 32, 10	24, 28,	
26	**Quantity of substance/the matter**	35, 6, 18, 31	27, 26, 18,	29, 14, 35, 18		15, 14, 29	2, 18, 40, 4	15, 20, 29		35, 29,	35, 14, 3	10, 36, 14, 3	35, 14	15, 2, 17, 40	14, 35, 34, 10	3, 35, 10, 40	3, 35, 31	3, 17, 39		34, 29, 16,	3, 35, 31	35	7, 18, 25	6, 3, 10, 24	24, 28, 35	35, 38, 18,	+	18, 3, 28, 40	13, 2, 28	33, 30	35, 33,	3, 35, 40, 39	29, 1, 35, 27	35, 29,	2, 32, 10, 25	15, 3, 29	3, 13, 27, 10	3, 27, 29, 18	8, 35	13, 29, 3, 27
27	**Reliability**	3, 8, 10, 40	3, 10, 8, 28	15, 9, 14, 4	15, 29, 28, 11	17, 10, 14, 16	32, 35,	3, 10, 14, 24	2, 35, 24	21, 35, 11, 28	8, 28, 10, 3	10, 24, 35, 19	35, 1, 16, 11		11, 28	2, 35, 3, 25	34, 27, 6,	3, 35, 10	11, 32, 13	21, 11, 27, 19	36, 23	21, 11, 26, 31	10, 11, 35	10, 35, 29, 39	10, 28	10, 30, 4	21, 28, 40, 3	+	32, 3, 11, 23	11, 32, 1	27, 35, 2,	35, 2, 40, 26		27, 17, 40	1, 11	13, 35, 8, 24	13, 35, 1	27, 40, 28	11, 13, 27	1, 35, 29, 38
28	**Measurement accuracy**	32, 35,	28, 35,	28, 26, 5,	32, 28, 3,	26, 28,	26, 28,	32, 13, 6		28, 13, 32, 24	32, 2	6, 28, 32	6, 28, 32	32, 35, 13	28, 6, 32	28, 6, 32	10, 26, 24	6, 19, 28, 24	6, 1, 32	3, 6, 32		3, 6, 32	26, 32, 27	10, 16, 31, 28		24, 34,	2, 6, 32	5, 11, 1, 23	+		28, 24,	3, 33, 39, 10	6, 35, 25, 18	1, 13, 17, 34	1, 32, 13, 11	13, 35, 2	27, 35, 10,	26, 24,	28, 2, 10, 34	10, 34, 28, 32
29	**Manufacturing precision**	28, 32, 13,	28, 35,	10, 28, 29, 37	2, 32, 10	28, 33,	2, 29, 18, 36	32, 23, 2	25, 10, 35	10, 28, 32	28, 19, 34, 36	3, 35	32, 30, 40	30, 18	3, 27	3, 27, 40		19, 26	3, 32	32, 2		32, 2	13, 32, 2	35, 31, 10, 24		32, 26,	32, 30	11, 32, 1		+	26, 28, 10,	4, 17, 34, 26		1, 32, 35, 23	25, 10		26, 2, 18		26, 28, 18,	10, 18, 32, 39
30	**Object-affected harmful factors**	22, 21, 27, 39	2, 22, 13, 24	17, 1, 39, 4	1, 18	22, 1, 33, 28	27, 2, 39, 35	22, 23,	34, 39, 19,	21, 22, 35, 28	13, 35, 39, 18	22, 2, 37	22, 1, 3, 35	35, 24,	18, 35, 37, 1	22, 15, 33, 28	17, 1, 40, 33	22, 33,	1, 19, 32, 13	1, 24, 6, 27	10, 2, 22, 37	19, 22, 31, 2	21, 22, 35, 2	33, 22, 19,	22, 10, 2	35, 18, 34	35, 33,	27, 24, 2,	28, 33,	26, 28, 10,	+		24, 35, 2	2, 25, 28, 39	35, 10, 2	35, 11, 22, 31	22, 19, 29, 40	22, 19, 29, 40	33, 3, 34	22, 35, 13,
31	**Object-generated harmful factors**	19, 22, 15, 39	35, 22, 1,	17, 15, 16, 22		17, 2, 18, 39	22, 1, 40	17, 2, 40	30, 18, 35, 4	35, 28, 3,	35, 28, 1,	2, 33, 27, 18	35, 1	35, 40,	15, 35, 22, 2	15, 22, 33, 31	21, 39, 16, 22	22, 35, 2,	19, 24, 39, 32	2, 35, 6	19, 22, 18	2, 35, 18	21, 35, 2, 22	10, 1, 34	10, 21, 29	1, 22	3, 24, 39, 1	24, 2, 40, 39	3, 33, 26	4, 17, 34, 26		+					19, 1, 31	2, 21, 27, 1	2	22, 35, 18,
32	**Ease of manufacture**	28, 29, 15,	1, 27, 36, 13	1, 29, 13, 17	15, 17, 27	13, 1, 26, 12	16, 40	13, 29, 1, 40	35	35, 13, 8, 1	35, 12	35, 19, 1, 37	1, 28, 13, 27	11, 13, 1	1, 3, 10, 32	27, 1, 4	35, 16	27, 26, 18	28, 24,	28, 26,	1, 4	27, 1, 12, 24	19, 35	15, 34, 33	32, 24, 18,	35, 28,	35, 23, 1,		1, 35, 12, 18		24, 2		+	2, 5, 13, 16	35, 1, 11, 9	2, 13, 15	27, 26, 1	6, 28, 11, 1	8, 28, 1	35, 1, 10, 28
33	**Ease of operation**	25, 2, 13, 15	6, 13, 1, 25	1, 17, 13, 12		1, 17, 13, 16	18, 16, 15, 39	1, 16, 35, 15	4, 18, 39, 31	18, 13, 34	28, 13, 35	2, 32, 12	15, 34, 29, 28	32, 35, 30	32, 40, 3,	29, 3, 8, 25	1, 16, 25	26, 27, 13	13, 17, 1, 24	1, 13, 24		35, 34, 2,	2, 19, 13	28, 32, 2,	4, 10, 27, 22	4, 28, 10, 34	12, 35	17, 27, 8, 40	25, 13, 2, 34	1, 32, 35, 23	2, 25, 28, 39		2, 5, 12	+	12, 26, 1, 32	15, 34, 1, 16	32, 26, 12,		1, 34, 12, 3	15, 1, 28
34	**Ease of repair**	2, 27, 35, 11	2, 27, 35, 11	1, 28, 10, 25	3, 18, 31	15, 13, 32	16, 25	25, 2, 35, 11	1	34, 9	1, 11, 10	13	1, 13, 2, 4	2, 35	11, 1, 2, 9	11, 29, 28, 27	1	4, 10	15, 1, 13	15, 1, 28, 16		15, 10, 32, 2	15, 1, 32, 19	2, 35, 34, 27		32, 1, 10, 25	2, 28, 10, 25	11, 10, 1, 16	10, 2, 13	25, 10	35, 10, 2, 16		1, 35, 11, 10	1, 12, 26, 15	+	7, 1, 4, 16	35, 1, 13, 11		34, 35, 7,	1, 32, 10
35	**Adaptability or versatility**	1, 6, 15, 8	19, 15, 29, 16	35, 1, 29, 2	1, 35, 16	35, 30,	15, 16	15, 35, 29		35, 10, 14	15, 17, 20	35, 16	15, 37, 1, 8	35, 30, 14	35, 3, 32, 6	13, 1, 35	2, 16	27, 2, 3, 35	6, 22, 26, 1	19, 35, 29, 13		19, 1, 29	18, 15, 1	15, 10, 2, 13		35, 28	3, 35, 15	35, 13, 8, 24	35, 5, 1, 10		35, 11, 32, 31		1, 13, 31	15, 34, 1, 16	1, 16, 7, 4	+	15, 29, 37, 28	1	27, 34, 35	35, 28, 6,
36	**Device complexity**	26, 30,	2, 26, 35, 39	1, 19, 26, 24	26	14, 1, 13, 16	6, 36	34, 26, 6	1, 16	34, 10, 28	26, 16	19, 1, 35	29, 13, 28, 15	2, 22, 17, 19	2, 13, 28	10, 4, 28, 15		2, 17, 13	24, 17, 13	27, 2, 29, 28		20, 19, 30, 34	10, 35, 13, 2	35, 10, 28, 29		6, 29	13, 3, 27, 10	13, 35, 1	2, 26, 10, 34	26, 24, 32	22, 19, 29, 40	19, 1	27, 26, 1,	27, 9, 26, 24	1, 13	29, 15, 28, 37	+	15, 10, 37, 28	15, 1, 24	12, 17, 28
37	**Difficulty of detecting and measuring**	27, 26,	6, 13, 28, 1	16, 17, 26, 24	26	2, 13, 18, 17	2, 39, 30, 16	29, 1, 4, 16	2, 18, 26, 31	3, 4, 16, 35	30, 28,	35, 36,	27, 13, 1, 39	11, 22, 39, 30	27, 3, 15, 28	19, 29, 39, 25	25, 34, 6,	3, 27, 35, 16	2, 24, 26	35, 38	19, 35, 16	18, 1, 16, 10	35, 3, 15, 19	1, 18, 10, 24	35, 33,	18, 28, 32, 9	3, 27, 29, 18	27, 40,	26, 24,		22, 19, 29, 28	2, 21	5, 28, 11, 29	2, 5	12, 26	1, 15	15, 10, 37, 28	+	34, 21	35, 18
38	**Extent of automation**	28, 26, 18,	28, 26,	14, 13, 17, 28	23	17, 14, 13		35, 13, 16		28, 10	2, 35	13, 35	15, 32, 1, 13	18, 1	25, 13	6, 9		26, 2, 19	8, 32, 19	2, 32, 13		28, 2, 27	23, 28	35, 10, 18, 5	35, 33	24, 28,	35, 13	11, 27, 32	28, 26, 10,	28, 26, 18,	2, 33	2	1, 26, 13	1, 12, 34, 3	1, 35, 13	27, 4, 1, 35	15, 24, 10	34, 27, 25	+	5, 12, 35, 26
39	**Productivity**	35, 26,	28, 27, 15,	18, 4, 28, 38	30, 7, 14, 26	10, 26, 34, 31	10, 35, 17, 7	2, 6, 34, 10	35, 37, 10,		28, 15, 10, 36	10, 37, 14	14, 10, 34, 40	35, 3, 22, 39	29, 28, 10,	35, 10, 2, 18	20, 10, 16, 38	35, 21, 28, 10	26, 17, 19, 1	35, 10, 38, 19	1	35, 20, 10	28, 10, 29, 35	28, 10, 35, 23	13, 15, 23		35, 38	1, 35, 10, 38	1, 10, 34, 28	18, 10, 32, 1	22, 35, 13,	35, 22, 18,	35, 28, 2,	1, 28, 7, 10	1, 32, 10, 25	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	5, 12, 35, 26	+

ANNEXURE C: 40 PRINCIPLES OF TRIZ (Source: Altshuller, 2007)

PRINCIPLES	
1	Segmentation
2	Extraction
3	Local Quality
4	Asymmetry
5	Consolidation
6	Universality
7	Nesting (Matrioshka)
8	Counterweight
9	Prior Counteraction
10	Prior Action
11	Cushion in Advance
12	Equipotentiality
13	Do It in Reverse
14	Spheroidality
15	Dynamicity
16	Partial or Excessive Action
17	Transition Into a New Dimension
18	Mechanical Vibration
19	Periodic Action
20	Continuity of Useful Action
21	Rushing Through
22	Convert Harm into Benefit
23	Feedback
24	Mediator
25	Self Service
26	Copying
27	Dispose
28	Replacement of Mechanical System
29	Pneumatic or Hydraulic Construction
30	Flexible Films of Thin Membranes
31	Porous Materials
32	Changing the Color
33	Homogeneity
34	Rejecting and Regenerating Parts
35	Transformation Properties
36	Phase Transition
37	Thermal Expansion
38	Accelerated Oxidation
39	Inert Environment
40	Composite Materials

ANNEXURE D: FMEA SEVERITY, OCCURRENCE AND DETECT RATING (Source: (Yang and El Haik, 2003)

Rating	Severity of effect	Likelihood of occurrence	Ability to detect
10	Hazardous without warning	Very high; failure is almost inevitable	Cannot detect
9	Hazardous with warning		Very remote chance of detection
8	Loss of primary function	High; repeated failures	Remote chance of detection
7	Reduced primary function performance		Very low chance of detection
6	Loss of secondary function	Moderate; occasional failures	Low chance of detection
5	Reduced secondary function performance		Moderate chance of detection
4	Minor defect noticed by most customers		Moderately high chance of detection
3	Minor defect noticed by some customers	Low; relatively few failures	High chance of detection
2	Minor defect noticed by discriminating customers		Very high chance of detection
1	No effect unlikely	Remote: failure is detection	Almost certain

ANNEXURE E: ORTHORGONAL ARRAY SELECTOR (Source: Subbarao, 2011)

Number of Levels	Number of Parameters (P)																													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32
3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36	L36	L36	L36	L36								
4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32																					
5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50																			

ANNEXURE F: FORMULAE TO CALCULATE RELIABILITY (Source: (Korb, 2012)

Product Moment Correlation Equation

$$r_{xy} = \frac{\Sigma(X - \bar{X})(Y - \bar{Y})}{\sqrt{[\Sigma(X - \bar{X})^2][\Sigma(Y - \bar{Y})^2]}}$$

Where,

r_{xy} = Product Moment Correlation

X = 1st half of questionnaires

Y = 2nd half of questionnaires

Spearman Brown

$$r_{SB} = \frac{2r_{hh}}{1 + r_{hh}}$$

Where,

r_{SB} = Spearman-Brown reliability index

r_{hh} = r_{xy} = Product Moment Correlation

Cronbach Alpha

$$r_{\alpha} = \left(\frac{k}{k-1}\right)\left(1 - \frac{\Sigma\sigma_i^2}{\sigma^2}\right)$$

Where,

r_{α} = Cronbach Alpha reliability

ANNEXURE G: MAIN SURVEY QUESTIONNAIRE
(Source: Researcher's own construction)

INSTRUCTIONS

1. Please read each statement carefully & tick your selection
   (5 = Strongly Agree, 4 = Agree, 3 = Undecided, 2 = Disagree, 1 = Strongly Disagree)
2. Answer **ALL** questions in **Part A , Part B**
3. **Part C** question is **optional**.
4. Please returned **completed questionnaire& signed consent form** to vasen.subroyen@gmail.com, or vasens@armscor.co.za

PART A: DESIGNATION/POSITION (Please tick appropriate box that reveals your position)

☐ SANDF OFFICER
☐ SCIENTIST/ENGINEER
☐ PROJECT MANAGER
☐ TECHNICAL SUPPORT[1]

[1] Includes technicians, artisans, administration, quality support etc.

PART B (5 = Strongly Agree, 4 = Agree, 3 = Undecided, 2 = Disagree, 1 = Strongly Disagree)

		1	2	3	4	5
1	Execution of defence technology projects are generally technically high risk in nature, so it is expected that additional unplanned resources may be required	☐	☐	☐	☐	☐
2	Due to a high level of uncertainty that is involved in the execution of defence technology projects, deadlines may have to be extended to successfully complete the project	☐	☐	☐	☐	☐
3	Defence technology project execution processes vary between projects so it is important that quality tools required to execute the project are flexible to accommodate such differences.	☐	☐	☐	☐	☐
4	Technical requirements to develop a concept are sometimes not clearly defined before development commences which results in the requirements being reviewed later with subsequent redesign of concept.	☐	☐	☐	☐	☐
5	Review of technical requirements during the development phase is allowable even it entails adding or changing requirements that leads to redesign of the concept.	☐	☐	☐	☐	☐
6	The method of trade-off analysis that requires improvement of one design characteristic (eg. armour protection/ additional weight) that leads to a deterioration of another characteristic (eg. mobility/performance) is practised to optimise a concept.	☐	☐	☐	☐	☐
7	Trial & Error method which involves back and forth iterations to a design is commonly applied to improve a design.	☐	☐	☐	☐	☐
8	Selection of the best design from a group of potential candidate designs should be confirmed by evaluating each candidate through comparative testing.	☐	☐	☐	☐	☐
9	Increasing the number of test samples is a common method to improve confidence in test data of the design.	☐	☐	☐	☐	☐
10	Quality inspection methods applied upon completion of a deliverable during the development phase are adequate to ensure that the concept satisfies the requirements	☐	☐	☐	☐	☐

11	Quality inspection of the concept at the end of the development phase may result in corrective action to improve the design.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
12	Redesign of a concept during the development phase may require replacement of components.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
13	Specially fabricated components that were replaced during redesign may never be re-used on another design.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
14	Redesigning a concept during the development phase may increase the risk of completing the project within the planned deadline.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
15	Engineering changes to the design during the development phase will require additional materials.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
16	The use of expensive superior grade materials to rapidly optimise a design during the development phase is considered acceptable.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
17	Certain processes such as test methods may be the same amongst several technology projects	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
18	Execution of defence technology projects are predictable so all required resources may be determined before commencement	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
19	Execution of defence technology projects are non-complex in nature, hence the project may be successfully completed within the planned deadline	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
20	Defence technology project execution processes are standard in nature amongst projects, thus stringent measures to control the quality of the output of the research can be applied	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
21	Requirements to develop a concept are clearly defined before development occurs ensuring no unplanned changes to designs at a later stage.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
22	Review of technical requirements during development phase is unacceptable as it could mean adding further requirements with subsequent redesign of the concept.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
23	The method of design trade-off analysis is seldom practised in defence technology project execution	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
24	Trial & Error method is least likely to be practised in defence technology project execution.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
25	Selection of the best design from a group of potential candidate's research can be determined by other methods rather than experiments	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
26	Large sample tests to improve accuracy in test results are overrated.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
27	Quality inspection methods applied at the completion of a deliverable is insufficient to ensure that the concept satisfies the requirements.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
28	Quality inspection at the end of the development phase ensures that no further corrective action may need to occur.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
29	Redesign of a concept during the development phase may not require replacement of components.	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐

30	Uniquely manufactured components that were discarded during redesign could be reused on another project	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
31	There is no risk in redesigning a concept during the development phase that will result in delaying the project.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
32	Engineering modifications to the design during the development phase may not require extra resources.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
33	The use of costly higher grade materials to swiftly enhance a design during the development phase is not an optimal solution.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
34	Test methods will continuously vary between technology projects	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐

35 Which of the following tools & techniques are currently being applied to improve designs or the processes during the execution of defence technology projects? Please tick applicable box(es).

- ☐ Brainstorming
- ☐ Design Reviews
- ☐ TRIZ Inventive Principles
- ☐ Value Stream Mapping
- ☐ Design of Experiments
- ☐ Design Failure Mode Effect Analysis
- ☐ Ishikawa Diagram
- ☐ Pugh Selection Matrix
- ☐ Axiomatic Design
- ☐ Quality Function Deployment
- ☐ P – Diagram
- ☐ Taguchi Robust Design

Refer to Appendix A for brief definitions of the above tools

PART C (Optional question)

36 Please list other tools/methods that are currently being applied to improve designs or processes (research, design, development activities) during execution of defence technology projects?

Please state which areas in defence technology project execution these tools are being used?

37

Please list challenges are experienced during the execution of defence technology projects that may result in project delays or the use of additional resources?

Please explain as to why these inefficiencies may impact on the execution of projects?

DEFINITION OF QUALITY ENGINEERING TOOLS

Brainstorming	A technique of solving specific problems, amassing information, stimulating creative thinking and develop new ideas by through participation in discussion
Design Reviews	Process whereby a design is evaluated against its requirements in order to verify the outcomes of previous activities and identify issues before committing to further work.
TRIZ Inventive Principles	Problem solving method based on logic & data, not intuition, which accelerates the project team's ability to solve problems creatively. It provides repeatability, predictability and reliability to its structure & algorithmic approach
Value Stream Mapping	A tool for achieving an efficient process by applying lean thinking to eliminate wastes and improve cycle time and quality in engineering.
Design of Experiments	A systematic method to determine the relationship between factors affecting a process/design and the output of that process/design. The information is needed in order to optimize the output.
Design Failure Mode Effect Analysis	Proactive tool used to identify failure modes during the early stages of the project when the design is still on paper .A process that is completed well in advance of a concept build.
Ishikawa Diagram	Known as a cause & effect diagram or fishbone diagram which is a visualization tool for categorizing the potential causes of a problem in order to identify its root causes
Pugh Selection Matrix	A decision matrix method used to rank the designs options according to requirements.
Axiomatic Design	System design method using matrix methods to systematically analyse the transformation of customer requirements into functional requirements, design parameters and process variables.
Quality Function Deployment	Structured approach to defining customer requirements into engineering (technical) requirements
P – Diagram	A parameter diagram used to analyse inputs, outputs, noise factors and control factors
Taguchi Robust Design	Systematic method using matrix to make a design more robust (less sensitive) against variations (uncontrollable noise factors)

ANNEXURE H: SURVEY DATA IN MICROSOFT EXCEL® (Source: Researcher's own construction)

Pearson Moment of correlation

CORRELATION OF ALL ITEMS

Σ(X - X̄)(Y - Ȳ)	762.78
Σ(X - X̄)2	2431.57
Σ (Y - Ȳ)2	1545.89
[Σ(X - X̄)2][Σ (Y - Ȳ)2]	3758940.59
CORRELATION (rxy)	0.393

CORRELATION OF ITEM WITH ITEM-TOTAL CORRELATION > 0.15

Σ(X - X̄)(Y - Ȳ)	996.750
Σ(X - X̄)2	2210.750
Σ (Y - Ȳ)2	1436.306
[Σ(X - X̄)2][Σ (Y - Ȳ)2]	3175312.507
CORRELATION (rxy)	0.520

Descriptive Statistics

Q1		Q2		Q3		Q4		Q5		Q6	
Mean	4.025	Mean	4	Mean	3.975	Mean	3.7	Mean	3.6	Mean	3.425
Standard Error	0.136285	Standard E	0.143222975	Standard Error	0.145389	Standard E	0.164862	Standard E	0.159326	Standard E	0.155611
Median	4	Median	4	Median	4	Median	4	Median	4	Median	4
Mode	4	Mode	4	Mode	4	Mode	4	Mode	4	Mode	4
Standard Deviation	0.861945	Standard D	0.905821627	Standard Devia	0.919518	Standard D	1.042679	Standard D	1.007663	Standard D	0.98417
Sample Variance	0.742949	Sample Va	0.820512821	Sample Varianc	0.845513	Sample Va	1.087179	Sample Va	1.015385	Sample Va	0.96859
Kurtosis	1.057356	Kurtosis	2.974062055	Kurtosis	4.436764	Kurtosis	0.830309	Kurtosis	0.835841	Kurtosis	-0.42231
Skewness	-1.06101	Skewness	-1.52522186	Skewness	-1.82351	Skewness	-1.06574	Skewness	-1.15859	Skewness	-0.62953
Range	3	Range	4	Range	4	Range	4	Range	4	Range	4
Minimum	2	Minimum	1	Minimum	1	Minimum	1	Minimum	1	Minimum	1
Maximum	5	Maximum	5	*Maximum*	5	Maximum	5	Maximum	5	Maximum	5
Sum	161	Sum	160	*Sum*	159	Sum	148	Sum	144	Sum	137
Count	40	Count	40	Count	40	Count	40	Count	40	Count	40

Q7		Q8		Q9		Q10		Q11		Q12		Q13	
Mean	3.325	Mean	3.9	Mean	3.825	Mean	3.375	Mean	3.625	Mean	3.7	Mean	2.95
Standard E	0.161672	Standard E	0.142325016	Standard E	0.155611	Standard Error	0.166747	Standard E	0.146268	Standard E	0.125064	Standard E	0.189297
Median	3.5	Median	4	Median	4	Median	4	Median	4	Median	4	Median	3
Mode	4	Mode	4	Mode	4	Mode	4	Mode	4	Mode	4	Mode	4
Standard D	1.022503	Standard D	0.900142439	Standard D	0.98417	Standard Devia	1.054599	Standard D	0.925078	Standard D	0.790975	Standard D	1.197219
Sample Va	1.045513	Sample Va	0.81025641	Sample Va	0.96859	Sample Varian	1.112179	Sample Va	0.855769	Sample Va	0.625641	Sample Va	1.433333
Kurtosis	-0.73143	Kurtosis	0.413162807	Kurtosis	1.069658	Kurtosis	-1.37219	Kurtosis	-0.34442	Kurtosis	1.075389	Kurtosis	-1.25328
Skewness	-0.25573	Skewness	-0.905919249	Skewness	-1.15957	Skewness	-0.27398	Skewness	-0.79588	Skewness	-1.36135	Skewness	-0.18261
Range	4	Range	3	Range	4	Range	3	Range	3	Range	3	Range	4
Minimum	1	Minimum	2	Minimum	1	Minimum	2	Minimum	2	Minimum	2	Minimum	1
Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5
Sum	133	Sum	156	Sum	153	Sum	135	Sum	145	Sum	148	Sum	118
Count	40	Count	40	Count	40	Count	40	Count	40	Count	40	Count	40

Q14		Q15		Q16		Q17		Q18		Q19		Q20		Q21	
Mean	3.85	Mean	3.525	Mean	3.175	Mean	3.475	Mean	3.625	Mean	4.05	Mean	3.525	Mean	3.25
Standard E	0.158316	Standard E	0.12397	Standard E	0.133433	Standard E	0.147577	Standard E	0.166747	Standard E	0.171532	Standard E	0.186009	Standard E	0.181694
Median	4	Median	4	Median	3	Median	4	Median	4	Median	4	Median	4	Median	4
Mode	4	Mode	4	Mode	3	Mode	4	Mode	4	Mode	5	Mode	4	Mode	4
Standard D	1.001281	Standard D	0.784056	Standard D	0.843907	Standard D	0.933356	Standard D	1.054599	Standard D	1.084861	Standard D	1.176424	Standard D	1.149136
Sample Va	1.002564	Sample Va	0.614744	Sample Va	0.712179	Sample Va	0.871154	Sample Va	1.112179	Sample Va	1.176923	Sample Va	1.383974	Sample Va	1.320513
Kurtosis	2.174297	Kurtosis	-0.24868	Kurtosis	-0.59677	Kurtosis	0.049379	Kurtosis	-0.93696	Kurtosis	-0.25076	Kurtosis	-0.68958	Kurtosis	-0.91649
Skewness	-1.45916	Skewness	-0.25472	Skewness	0.188784	Skewness	-0.91954	Skewness	-0.55444	Skewness	-0.99122	Skewness	-0.5603	Skewness	-0.52026
Range	4	Range	3	Range	3	Range	4	Range	3	Range	3	Range	4	Range	4
Minimum	1	Minimum	2	Minimum	2	Minimum	1	Minimum	2	Minimum	2	Minimum	1	Minimum	1
Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5
Sum	154	Sum	141	Sum	127	Sum	139	Sum	145	Sum	162	Sum	141	Sum	130
Count	40	Count	40	Count	40	Count	40	Count	40	Count	40	Count	40	Count	40

Q22		Q23		Q24		Q25		Q26		Q27		Q28	
Mean	3.625	Mean	3.375	Mean	3.425	Mean	2.775	Mean	3.35	Mean	2.975	Mean	3.4
Standard E	0.154785	Standard E	0.137223	Standard E	0.142719	Standard E	0.126529	Standard E	0.141195	Standard E	0.165976	Standard E	0.15525
Median	4	Median	4	Median	4	Median	3	Median	4	Median	3	Median	4
Mode	4	Mode	4	Mode	4	Mode	2	Mode	4	Mode	4	Mode	4
Standard D	0.978945	Standard D	0.867874	Standard D	0.902631	Standard D	0.80024	Standard D	0.892993	Standard D	1.049725	Standard D	0.981887
Sample Va	0.958333	Sample Va	0.753205	Sample Va	0.814744	Sample Va	0.640385	Sample Va	0.797436	Sample Va	1.101923	Sample Va	0.964103
Kurtosis	0.285015	Kurtosis	-0.99648	Kurtosis	-0.81906	Kurtosis	-0.02229	Kurtosis	-0.9756	Kurtosis	-1.31276	Kurtosis	-1.16133
Skewness	-0.88737	Skewness	-0.58451	Skewness	-0.31503	Skewness	0.753883	Skewness	-0.31724	Skewness	-0.08811	Skewness	-0.39004
Range	4	Range	3	Range	3	Range	3	Range	3	Range	4	Range	3
Minimum	1	Minimum	2	Minimum	2	Minimum	2	Minimum	2	Minimum	1	Minimum	2
Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5	Maximum	5
Sum	145	Sum	135	Sum	137	Sum	111	Sum	134	Sum	119	Sum	136
Count	40	Count	40	Count	40	Count	40	Count	40	Count	40	Count	40

Q29		Q30		Q31		Q32		Q33		Q34	
Mean	3.375	Mean	2.875	Mean	3.85	Mean	3.625	Mean	3	Mean	2.425
Standard E	0.132469	Standard E	0.139539	Standard E	0.162315	Standard E	0.137223	Standard E	0.129099	Standard E	0.147142
Median	3.5	Median	3	Median	4	Median	4	Median	3	Median	2
Mode	4	Mode	2	Mode	4	Mode	4	Mode	3	Mode	2
Standard D	0.837808	Standard D	0.882523	Standard D	1.02657	Standard D	0.867874	Standard D	0.816497	Standard D	0.930605
Sample Va	0.701923	Sample Va	0.778846	Sample Va	1.053846	Sample Va	0.753205	Sample Va	0.666667	Sample Va	0.866026
Kurtosis	-0.6976	Kurtosis	-1.25459	Kurtosis	-0.4767	Kurtosis	-0.20569	Kurtosis	-1.49573	Kurtosis	-0.57281
Skewness	-0.27107	Skewness	0.018407	Skewness	-0.73274	Skewness	-0.65418	Skewness	0	Skewness	0.631831
Range	3	Range	3	Range	3	Range	3	Range	2	Range	3
Minimum	2	Minimum	1	Minimum	2	Minimum	2	Minimum	2	Minimum	1
Maximum	5	Maximum	4	Maximum	5	Maximum	5	Maximum	4	Maximum	4
Sum	135	Sum	115	Sum	154	Sum	145	Sum	120	Sum	97
Count	40	Count	40	Count	40	Count	40	Count	40	Count	40

Responses

Responses	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17
Strongly Agree	28%	25%	23%	18%	10%	8%	10%	23%	20%	10%	10%	5%	5%	20%	8%	5%	5%
Agree	58%	63%	65%	55%	63%	53%	40%	58%	60%	50%	63%	75%	40%	63%	48%	30%	60%
Undecided	5%	3%	5%	13%	10%	18%	25%	8%	5%	8%	8%	5%	13%	5%	35%	43%	15%
Disagree	10%	8%	3%	10%	13%	20%	23%	13%	13%	33%	20%	15%	30%	8%	10%	23%	18%
Strongly disagree	0%	3%	5%	5%	5%	3%	3%	0%	3%	0%	0%	0%	13%	5%	0%	0%	3%

Q18	Q19	Q20	Q21	Q22	Q23	Q24	Q25	Q26	Q27	Q28	Q29	Q30	Q31	Q32	Q33	Q34
0%	0%	5%	8%	3%	0%	0%	0%	0%	5%	0%	0%	3%	0%	0%	0%	10%
25%	18%	20%	25%	15%	23%	20%	43%	23%	38%	28%	18%	38%	18%	15%	33%	58%
5%	3%	13%	10%	13%	20%	25%	40%	25%	15%	13%	33%	30%	8%	18%	35%	13%
53%	38%	43%	50%	58%	55%	48%	15%	48%	40%	53%	45%	30%	48%	58%	33%	20%
18%	43%	20%	8%	13%	3%	8%	3%	5%	3%	8%	5%	0%	28%	10%	0%	0%

Cronbach alpha, item-analysis values

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18
k	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33
SUM OF VARIATION	29.8675	29.7919	29.7675	29.5319	29.6019	29.6475	29.5725	29.8019	29.6475	29.5075	29.7575	29.9819	29.1944	29.6144	29.9925	29.8975	29.7425	29.5075
TOTAL VARIATION	176.848	171.224	173.5	173.349	174.484	175.148	178.828	175.619	172.678	187.19	177.328	174.699	180.524	172.409	179.448	188.56	185.3	174.928
Item-Total Correlation	0.632	0.660	0.507	0.557	0.514	0.449	0.252	0.476	0.521	-0.093	0.403	0.661	0.402	0.512	0.379	0.122	0.216	0.448

Q19	Q20	Q21	Q22	Q23	Q24	Q25	Q26	Q27	Q28	Q29	Q30	Q31	Q32	Q33	Q34
33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33
29.444375	29.2425	29.3044	29.6575	29.8575	29.7975	29.9675	29.8144	29.5175	29.6519	29.9075	29.8325	29.5644	29.8575	29.9419	29.7475
172.769375	177.798	175.649	172.228	181.29	176.148	189.96	181.484	185.75	177.494	179.04	192.99	174.909	180.828	188.924	197.648
0.524	0.227	0.524	0.564	0.267	0.530	-0.025	0.260	0.131	0.394	0.413	-0.084	0.489	0.263	-0.122	-0.246

Chi Square test

Observed Frequency (O)	Q5 Review of technical requirements			
Q1 Use of unplanned Resource	Disagree	Undecided	Agree	Total
Disagree	3		1	4
Undecided			2	2
agree	4	4	26	34
	7	4	29	40

Expected frequency (E)	Q5 Review of technical requirements			
Q1 Use of unplanned Resource	Disagree	Undecided	Agree	Total
disagree	0.7	0.4	2.9	4
Undecided	0.35	0.2	1.45	2
agree	5.95	3.4	24.65	34
	7	4	29	40

O-E	2.3	-0.4	-1.9	
	-0.35	-0.2	0.55	
	-1.95	0.6	1.35	
(O-E)2	5.29	0.16	3.61	
	0.1225	0.04	0.3025	
	3.8025	0.36	1.8225	
X2= (O-E)2 /E	7.557143	0.4	1.244827586	9.201970443
	0.35	0.2	0.20862069	0.75862069
	0.639076	0.105882	0.073935091	0.818893074
			X2=	10.77948421

Level of Significance	0.05
Chi Square test statistic	10.77948
Degrees of freedom	4
Critical Value	9.488
P-value	0.0434

Observed F	Q6 Trade Off analysis Methods is practised			
Q14	Disagree	Undecided	Agree	Total
Disagree	4		1	5
Undecided	1		1	2
agree	4	7	22	33
Total	9	7	24	40

Expected f	Q6 Trade Off analysis Methods is practised			
Q14	Disagree	Undecided	Agree	Total
disagree	1.125	0.875	3	5
Undecided	0.45	0.35	1.2	2
agree	7.425	5.775	19.8	33
Total	9	7	24	40

O-E	2.875	-0.875	-2	
	0.55	-0.35	-0.2	
	-3.425	1.225	2.2	
(O-E)2	8.265625	0.765625	4	
	0.3025	0.1225	0.04	
	11.73063	1.500625	4.84	
X2	7.347222	0.875	1.333333	9.555556
	0.672222	0.35	0.033333	1.055556
	1.579882	0.259848	0.244444	2.084175
			X2 =	12.69529

Level of Si	0.05
Chi Square	12.69529
Degrees of	4
Critical Val	9.488
P-value	0.021757

Observed F	Q6 Trade Off analysis Methos is practised			
Q12	Disagree	Undecided	Agree	Total
Disagree	5		1	6
Undecided		1	1	2
agree	4	6	22	32
	9	7	24	40

Expected f	Q6 Trade Off analysis Methos is practised			
Q12	Disagree	Undecided	Agree	Total
disagree	1.35	1.05	3.6	6
Undecided	0.45	0.35	1.2	2
agree	7.2	5.6	19.2	32
	9	7	24	40

O-E	3.65	-1.05	-2.6	
	-0.45	0.65	-0.2	
	-3.2	0.4	2.8	
(O-E)2	13.3225	1.1025	6.76	
	0.2025	0.4225	0.04	
	10.24	0.16	7.84	
X2= (O-E)2	9.868519	1.05	1.877778	12.7963
	0.45	1.207143	0.033333	1.690476
	1.422222	0.028571	0.408333	1.859127
			X2=	16.3459

Level of Si	0.05
Chi Square	16.3459
Degrees of	4
Critical Val	9.488
P-value	0.005032

Observed Freq	Q9 Large Sample testing is practised			
Q14 Redesign	Disagree	Undecided	Agree	Total
Disagree	4		1	5
Undecided			2	2
agree	2	2	29	33
	6	2	32	40

Expected freq	Q9 Large Sample testing is practised			
Q14 Redesign	Disagree	Undecided	Agree	Total
disagree	0.75	0.25	4	5
Undecided	0.3	0.1	1.6	2
agree	4.95	1.65	26.4	33
	6	2	32	40

O-E	3.25	-0.25	-3	
	-0.3	-0.1	0.4	
	-2.95	0.35	2.6	
(O-E)2	10.5625	0.0625	9	
	0.09	0.01	0.16	
	8.7025	0.1225	6.76	
X2= (O-E)2 /E	14.08333	0.25	2.25	16.58333
	0.3	0.1	0.1	0.5
	1.758081	0.074242	0.256060606	2.088384
		X2=		19.17172

Level of Signifi	0.05
Chi Square tes	19.17172
Degrees of free	4
Critical Value	9.488
P-value	0.000976

Observed F	Q8 Multiple comparitive testing is practised			
Q2 Projec	Disagree	Undecided	Agree	Total
Disagree	2		2	4
Undecided	1			1
agree	2	3	30	35
	5	3	32	40

Expected f	Q8 Multiple comparitive testing is practised			
Q2 Projec	Disagree	Undecided	Agree	Total
disagree	0.5	0.3	3.2	4
Undecided	0.125	0.075	0.8	1
agree	4.375	2.625	28	35
	5	3	32	40

O-E	1.5	-0.3	-1.2	
	0.875	-0.075	-0.8	
	-2.375	0.375	2	
(O-E)2	2.25	0.09	1.44	
	0.765625	0.005625	0.64	
	5.640625	0.140625	4	
X2= (O-E)2	4.5	0.3	0.45	5.25
	6.125	0.075	0.8	7
	1.289286	0.053571	0.142857	1.485714
		X2=		13.73571

Level of Si	0.05
Chi Square	13.73571
Degrees of	4
Critical Val	9.488
P-value	0.013634

Observed F	Q14 Redesign results in project delays			
Q7 Trial &	Disagree	Undecided	Agree	Total
Disagree	1	1	8	10
Undecided	4		6	10
agree		1	19	20
	5	2	33	40

Expected f	Q14 Redesign results in project delays			
Q7 Trial &	Disagree	Undecided	Agree	Total
disagree	1.25	0.5	8.25	10
Undecided	1.25	0.5	8.25	10
agree	2.5	1	16.5	20
	5	2	33	40

O-E	-0.25	0.5	-0.25	
	2.75	-0.5	-2.25	
	-2.5	0	2.5	
(O-E)2	0.0625	0.25	0.0625	
	7.5625	0.25	5.0625	
	6.25	0	6.25	
X2= (O-E)2	0.05	0.5	0.007576	0.557576
	6.05	0.5	0.613636	7.163636
	2.5	0	0.378788	2.878788
		X2=		10.6

Level of Si	0.05
Chi Square	10.6
Degrees of	4
Critical Val	9.488
P-value	0.10738

Observed F	Q12 Redesign require replacement of components			
Q8 Multipl	Disagree	Undecided	Agree	Total
Disagree	4		1	5
Undecided			3	3
agree	4	2	26	32
	8	2	30	40

Expected f	Q12 Redesign require replacement of components			
Q8 Multipl	Disagree	Undecided	Agree	Total
disagree	1	0.25	3.75	5
Undecided	0.6	0.15	2.25	3
agree	6.4	1.6	24	32
	8	2	30	40

O-E	3	-0.25	-2.75	
	-0.6	-0.15	0.75	
	-2.4	0.4	2	
(O-E)2	9	0.0625	7.5625	
	0.36	0.0225	0.5625	
	5.76	0.16	4	
X2= (O-E)2	9	0.25	2.016667	11.26667
	0.6	0.15	0.25	1
	0.9	0.1	0.166667	1.166667
		X2=		13.43333

Level of Si	0.05
Chi Square	13.43333
Degrees of	4
Critical Val	9.488
P-value	0.014404

Observed F	Q11 Post deliverable quality inspection results in corrective action			
Q14 Redes	Disagree	Undecided	Agree	Total
Disagree	4		1	5
Undecided		1	1	2
agree	4	2	27	33
	8	3	29	40

Expected f	Q11 Post deliverable quality inspection results in corrective action			
Q14 Redes	Disagree	Undecided	Agree	Total
disagree	1	0.375	3.625	5
Undecided	0.4	0.15	1.45	2
agree	6.6	2.475	23.925	33
	8	3	29	40

O-E	3	-0.375	-2.625	
	-0.4	0.85	-0.45	
	-2.6	-0.475	3.075	
(O-E)2	9	0.140625	6.890625	
	0.16	0.7225	0.2025	
	6.76	0.225625	9.455625	
X2= (O-E)2	9	0.375	1.900862	11.27586
	0.4	4.816667	0.139655	5.356322
	1.024242	0.091162	0.395219	1.510623
		X2=		18.14281

Level of Si	0.05
Chi Square	18.14281
Degrees of	4
Critical Val	9.488
P-value	0.001639

Observed f	Q11 Post deliverable quality inspection results in corrective action			
Q12 Redes	Disagree	Undecided	Agree	Total
Disagree	5		1	6
Undecided			2	2
agree	3	3	26	32
	8	3	29	40

Expected f	Q11 Post deliverable quality inspection results in corrective action			
Q12 Redes	Disagree	Undecided	Agree	Total
disagree	1.2	0.45	4.35	6
Undecided	0.4	0.15	1.45	2
agree	6.4	2.4	23.2	32
	8	3	29	40

O-E	3.8	-0.45	-3.35	
	-0.4	-0.15	0.55	
	-3.4	0.6	2.8	
(O-E)2	14.44	0.2025	11.2225	
	0.16	0.0225	0.3025	
	11.56	0.36	7.84	
X2= (O-E)2	12.03333	0.45	2.579885	15.06322
	0.4	0.15	0.208621	0.758621
	1.80625	0.15	0.337931	2.294181
			X2=	18.11602

Level of Sig	0.05
Chi Square	18.11602
Degrees of	4
Critical Val	9.488
P-value	0.001835

Voluntary questions Data

RESPONDENTS	PROJECT MANAGER	SANDF OFFICER	RESEARCH SCIENTIST/ENGINEER	TECHNICAL SUPPORT
1				1
2		1		
3		1		
4			1	
5				1
6	1			
7			1	
8	1			
9			1	
10	1			
11				1
12			1	
13				1
14	1			
15	1			
16				1
17				1
18			1	
19	1			
20				1
21			1	
22		1		
23				1
24	1			
25	1			
26	1			
27				1
28			1	
29	1			
30	1			
31	1			
32	1			
33	1			
34			1	
35	1			
36	1			
37				1
38	1			
39				1
40	1			

RESPONDENTS	BRAINSTOR	ISHIKAWA	DESIGN REVIEW	PUGH	TRIZ	AXIOMATIC	VSM	QFD	DOE	P-DIAGRAM	DFMEA	TAGUCHI
1	1								1			
2	1		1					1	1	1		
3	1		1					1				
4	1		1					1				
5	1											
6	1		1					1	1			
7	1		1						1			
8	1		1									
9	1		1					1	1		1	
10			1								1	
11			1					1			1	
12	1	1	1	1		1	1		1		1	
13			1					1			1	
14	1		1	1				1	1			
15	1	1	1				1				1	
16	1	1							1		1	
17			1					1	1		1	
18	1		1	1		1		1	1			
19	1		1					1	1			
20	1	1	1					1	1		1	
21	1	1						1				
22	1		1						1		1	
23	1	1	1								1	
24	1		1								1	
25	1		1						1		1	
26	1		1				1	1	1		1	
27												
28	1		1								1	
29			1				1		1		1	
30		1	1									
31												
32												
33	1		1						1		1	
34	1	1	1	1	1	1		1	1	1	1	1
35	1	1										
36	1	1	1		1			1	1		1	
37			1									
38	1	1			1		1		1		1	
39	1		1				1		1			
40	1		1								1	

Simulation & Modelling	Matlab, Monte Carlo	4	30.8%
Manufacturing Techniques	3-D printing, Build proof of concept model	2	15.4%
Testing & Evaluation		3	23.1%
Analysis Tools	Requirement analysis tools CORE, DOORs and Systems Architect, MindManager, Functional Hazard Analysis and Fault Tree Analysis. Use of Architectural Mitigation Techniques, Objective matrix, design reviews, design failure mode and effect analysis (FMEA)	5	38.5%
Management Tools	MS Project, PMBOK, Contracts, Request for Information	4	30.8%

Requirement challenges	8	42.11%	requirements not defined, scope creep, change in requirements
Unavailability of resources	11	57.89%	Obsolete equipment, expensive equipment, unavailability of equipment and human resources, Lack of of expertise
High Level Management Challenges	7	36.84%	Project Management issues, Change management issues, Transformation issues , Diversity of suppliers, Strategic Management issues, SHEQ issues, Logistic issues
Lack of Funding	1	5.26%	
Project Delays	2	10.53%	

ANNEXURE I: ELECTRONIC COPY OF FUNCTIONAL FRAMEWORK
(Source: Researcher’s own construction)

(Compact Disc)

ANNEXURE J: PERCEPTION STUDY QUESTIONNAIRE (Source: Researcher's own construction)

DUT DURBAN UNIVERSITY OF TECHNOLOGY

PERCEPTION SURVEY QUESTIONAIRE

NAME: (Optional)_____

ORGANIZATION: (Optional) _____

INSTRUCTIONS

1. **Please read each statement carefully & tick your selection**
2. **Answer all questions**

For questions 1 to 6 Please select only one viewpoint from selection below

1. When reviewing the Model, was it easy to navigate to all the methods.

☐ Definitely

☐ Yes, however it could be improved
Please explain how it can be improved:____

____

____

____

☐ Not sure

☐ No

2. The Model contains adequate information that explains how each method can be implemented

☐ Definitely

☐ Yes, however it could be improved
Please explain how it can be improved:____

____

____

☐ Not sure

☐ No

1

3. There are similar low cost functional models available to optimise Defence technology R & D projects that encompass these Quality Management and Engineering methods into a single program.

☐ Yes, there are.
Please list similar functional models:____

____

____

____

☐ Not sure

☐ No

4. I would be prepared to use this Model during the execution of my defence technology R & D projects.

☐ Definitely

☐ Yes, I would, but would some improvements
Please explain how it can be improved:____

____

____

____

☐ Not sure

☐ No

5. I would require additional training to understand how to effectively implement the quality management and engineering methods in this model.

☐ Definitely Not

☐ Yes, I would require further training.
Please list which tools you would require further training____________________________

____

____

____

☐ Not sure

6. The quality management and engineering tools in this Model will aid in optimising defence technology project execution by reducing project delays and use of unplanned resources.

☐ Definitely

☐ Yes, however it could be improved
Please explain how it can be improved:____

____

____

____

☐ Not sure

☐ No

Please select any <u>one or more viewpoints</u> from selection below

7. In my opinion, what differentiates this Model from other Models is it's.....

☐ Design such as use of navigation buttons, flow diagrams, matrices, information blocks to explain and illustrate the methods

☐ Ability to be flexible where one method OR a combination of methods OR all methods can be applied to optimise defence technology R & D project execution

☐ Practical approach rather than theoretical or abstract were the methods in the Model can be implemented

☐ Other abilities

Please state other abilities:____

____

____

____

____

____

____

8. This Model provides a sound basis onto which other quality methods identified in future can be built into.

☐ Definitely

☐ Not sure

☐ No

9. **OPTIONAL QUESTION**

Please list other improvements to the Model that would guarantee a more effective Toolbox during implementation.

____

____

____

____

____

____

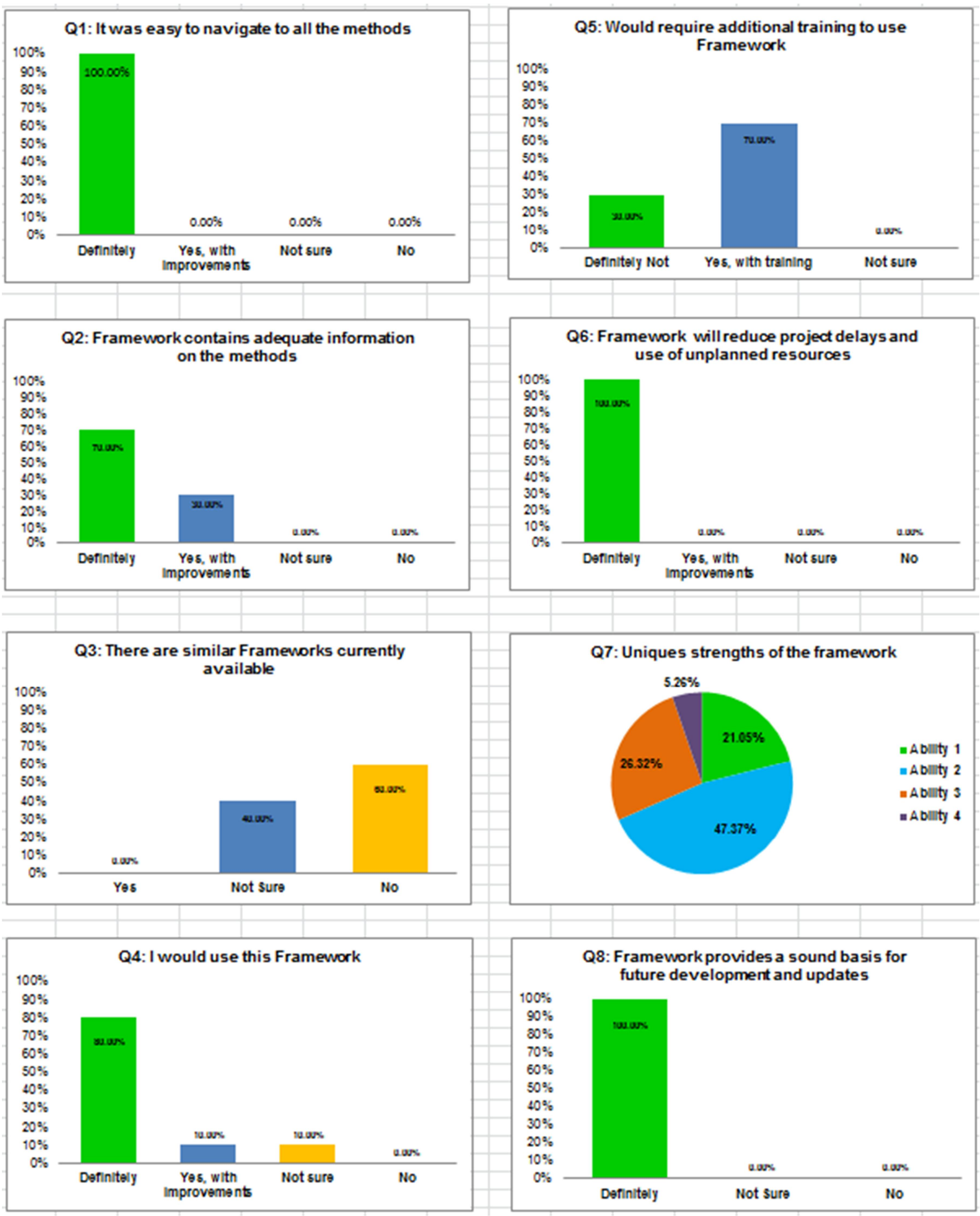
____

____

____

____

ANNEXURE K: PERCEPTION STUDY RESULTS (Source: Researcher's own construction)

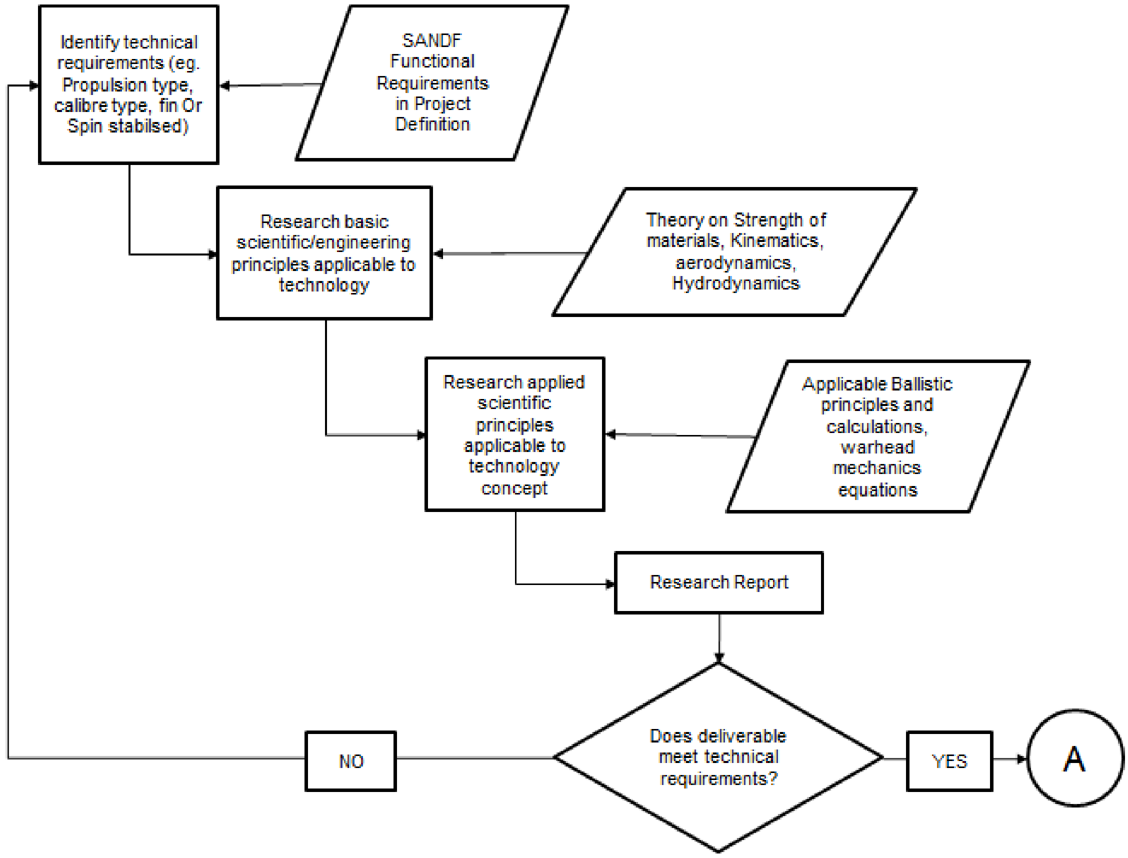


ANNEXURE L: LEGISLATION (Source: DOD, 1999)

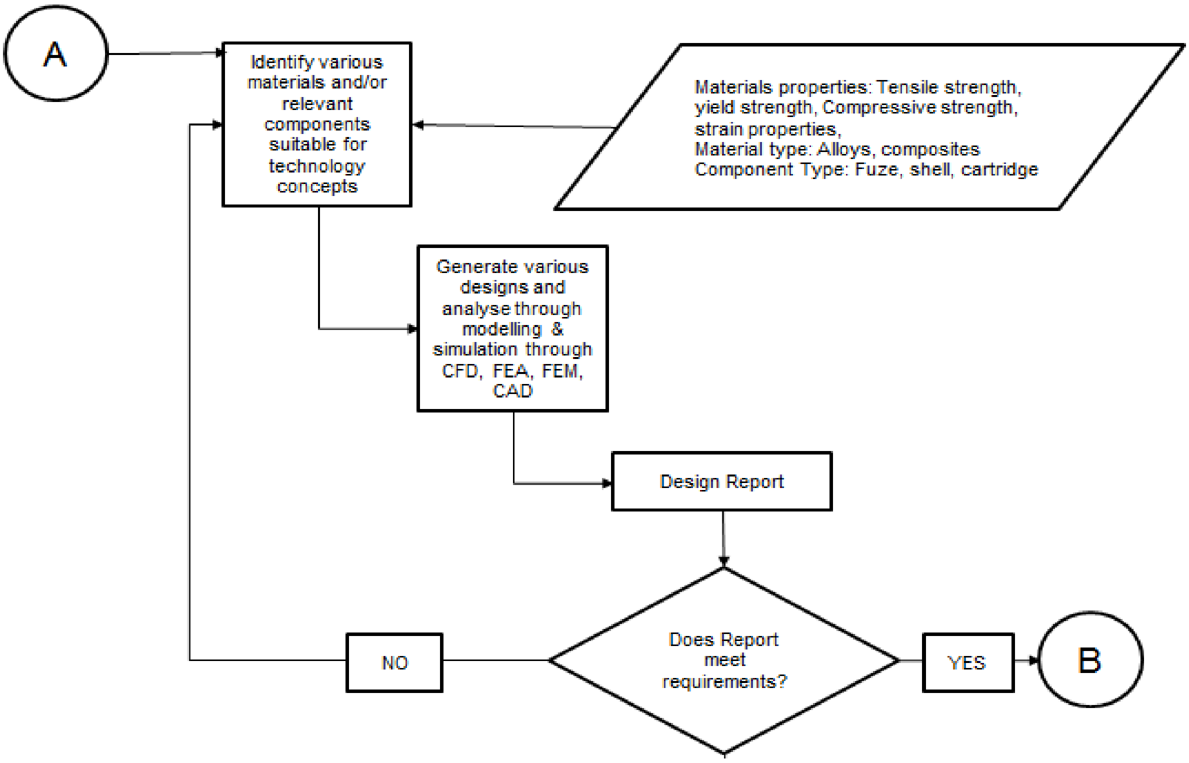
LEGISLATION	CONTROL	STRUCTURE	RESPONSIBLE DEPARTMENT
Conventional Arms Control Bill	Conventional Arms	NCACC DCAC	Department of Defence (DoD)
Armaments Development and Production Act (Act 57 of 1968)	Conventional Arms	NCACC DCAC	Department of Defence (DoD)
Non-Proliferation of Weapons of Mass Destruction (Act 87 of 1993)	Weapons of Mass Destruction and Dual-use Items	Non-Proliferation Council (NPC)	Department of Trade and Industry (DTI)
Explosives Act (Act 26 of 1956) Firearms and Ammunition Act (Act 75 of 1969) Teargas Act (Act 16 of 1964)	Explosives (Commercial and Military Applications) Commercial Arms and Ammunition	South African Police Service (SAPS) (Inspectorate of Explosives) South African Police Service (SAPS) (Central Firearms Register)	Ministry of Safety and Security Ministry of Safety and Security
Nuclear Energy Act (1993)	Nuclear Materials and Related Technology	Atomic Energy Corporation (AEC)	Department of Mineral and Energy Affairs

ANNEXURE M: Lower Level Defence Technology R & D Project Execution Activities Example (Source: Researcher's own construction)

1. DEFINE PHASE



2. DESIGN EVALUATION PHASE



3. TESTING EVALUATION PHASE