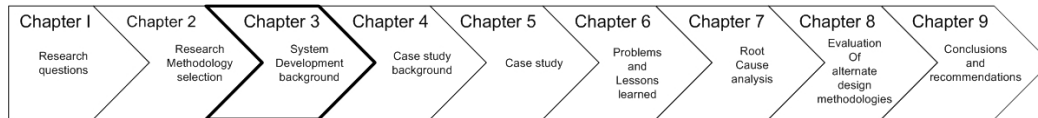*"A complex system that works is invariably found to have evolved from a simple system that works."*
John Gall, 1978

System – characteristics and properties
Systems Engineering
Systems engineering process
Project Management
Matrix organisational structure
Design influencing

In this chapter the researcher discusses the system characteristics and properties; an overview of systems engineering and systems engineering process, and an overview of the management structures for the management of the project resources. Design influencing is discussed and a design influencing model is developed.

Chapter 3   SYSTEM DEVELOPMENT BACKGROUND

In the previous chapter, the research approach and analysis methods have been discussed. In this chapter exploratory research will be used to provide the background needed to facilitate the achievement of the research objectives; optimising design influencing and evaluation of impact of a design change. By delving deeper into the design process, the research objective of optimisation of design influencing by dividing the design teams into two different mindset groups will be investigated. Introducing the dynamic effect of project management, prepares for the research question: *"Can models be established to depict the success/failure domain interactions in a dynamic project management environment?"*

To better understand why design influencing gives rise to iterations as well as the impact of design changes in a concurrent engineering environment, a brief overview, properties and main characteristics of the following will be discussed:

- **A system**
  A system's main properties and characteristics

- **Systems engineering**
  The systems engineering process and outcomes

- **Project Management**
  The project management process characteristics and constraints

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- **Matrix organizational structure**
  The matrix organizational structure, characteristics and constraints

- **Design influencing**
  The objectives of design influencing and effects on the system under development

During the system development process, the above interact continuously and impact on the development project performance.

These properties and characteristics will be playing a pivotal role in the case-study for the development of an anti-tank weapons system.

3.1   System

In chapter 1 an overall view and definitions of a system was given. The fundamental reason for developing a system is to perform a function or number of functions in a specific environment, (Sparrius, 2006), (Booch et al, 1998). According to Booch et al, (1998), a real system must have some dynamic dimension to them, and these dynamics are triggered by things that happen externally or internally. From this it can be deduced that a real system is dynamic and that there must be functional couplings between the different elements of the system for the system to be able to function as a whole entity.

3.1.1   Characteristics and Properties of a System

All systems exist in a multi-layer hierarchy, each top layer more complex than the one below. Each layer typically forms a system in its own right. Entities from the next lower layer form its constituent's components whereas an entity from the next higher layer forms its environment. Therefore we can conclude that each entity at any layer is both a system, a component of a system and part of an environment, (Sparrius, 2008). The hierarchical structure of a system is not its only characteristic. A system also exhibits emergent properties. The performance of a system is determined not only by the performance of its subsystems or components but also by their interaction. The emergence and hierarchy principles are fundamental to systems engineering and can be defined as follows (Sparrius 2008):

- **Emergence Principle and emergent properties**

  In philosophy, systems theory, science, and art, emergence is the way complex systems and patterns arise out of a multiplicity of relatively simple interactions. Emergence is central to the theories of integrative levels and of complex systems.

Sparrius, (2008), states that: *"Every system exhibit emergent properties that derive from its components and their interaction but cannot be reduced to them. These emergent properties are meaningful only when attributed to the system, not its components"*.

Emergent properties are the principle that whole entities exhibit properties that are meaningful only when attributed to the whole not to its parts. In other words an integrated system's worth is more than the sum of its components. None of the individual subsystems, components, operating system and software of a PC can perform a word processing function, yet the integrated PC is imminently suitable for word processing (Sparrius, 2008). Sommerville, (1996), states that emergent properties are properties of the system as a whole, rather than properties that can be derived from the properties of components of a system. Emergent properties are a consequence of the relationships between system components, they can therefore only be assessed and measured once the components have been integrated into a system. In this research, these relationships between system components will be referred to as functional couplings.

- **Hierarchy Principle**

  Sparrius (2008), also states that: *"All systems exist in a hierarchy. Each layer in a hierarchy is a system in its own right. The next higher layer is its environment and the next lower layer its components. The principles governing one hierarchical layer are also governing the other layers. Emergent properties distinguish layers"*. In figure 6, Hitchins (1992), illustrates a hypothetical k-level hierarchy system, and the principle that whole entities exhibit properties which are meaningful only when attributed to the whole and not its parts. He states that every system exhibits emergent properties which derive from its component activities and structure but cannot be reduced to them. He also describes the hierarchy principle according to which entities are meaningfully viewed as wholes and further states that in a hierarchy, emergent properties denotes levels. Hitchins (1992) defines the primary task of systems engineering as: "*To identify, realize and maintain the requisite emergent properties of a system to meet customer's and end-user's needs*". From the above, it can be deduced that there are always functional couplings between system components, its parents and their parents until the highest system level in the hierarchy.
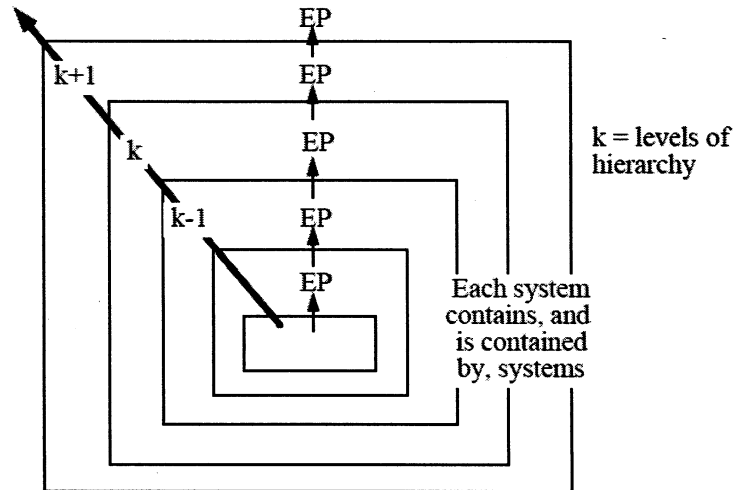
Figure 6: System emergent and hierarchy properties

Source: Hitchins, (1992).

From the above it can also be deduced that the consequences of design influencing or design change of one component in a system has a direct impact on the system as a whole as a result of the functional couplings. This will be further discussed and analysed in chapter 7.

3.1.2   System dynamics

"A perfectly static system would be intensely uninteresting because nothing ever happens."
Booch et al, (1998).

Design influencing has the connotation of design change or design amendment. Since a system is more than the sum of its components to reveal the emergent properties, design influencing must not only focus on the design item itself but also study the influence of any design change on the system's behaviour and dynamic stability

From the previous paragraphs, discussions and literature reviews, it can be concluded that real systems must be dynamic. Bertalanffy, (1968), describes a mathematical model of a system as a set of variables that maintain functional relations through time.

Viljoen, (2007) describes Bertalanffy's equations for a dynamic system by means of a set of differential equations for each state as a function of all the system elements. On analysis of the equations for a system in equilibrium, he found that the roots (real or imaginary), determine the dynamic response and stability of the

system. A complete analysis of the equations by Viljoen, (2007), is provided in appendix A.

Viljoen (2007), further shows that for a system in equilibrium, the time derivative in the equations are equal to zero and that the equations can then be solved algebraically. He then proceeds to introduce a new variable, representing a modification or addition to an already stable system and finds a general solution for the modified system. He finds that a number of conclusions can be drawn from inspection of the roots of the equation.

- If all the real parts are negative, the system is stable.

- If the roots are imaginary with negative real parts, the system is asymptotically stable.

- If there are any real roots that are positive, the system is unstable.

Detail mathematical interpretation of Viljoen's (2007) findings, falls outside the scope of this research.

A consequence of the findings by Viljoen (2007), is that a change or modification to a component in a system must be approached with care, since a change or modification to one component in a system may result in the system or the affected portion of the system becoming unstable.

However from a design influencing point of view during system development, a change of the dynamic characteristics of one component of a system, can have an impact on the integrated system's dynamic performance as a result of the emergent properties, (Hitchins, 1992).

Also from Viljoen's (2007) analysis, it can be concluded that a modification or addition to an already optimally working system, is not trivial and extreme care must be taken since the delicate balance of all the elements comprising the system, can be disturbed affecting the performance of the revised system. Also a change to one element in a system very often has an impact on other elements in the system, due to the functional couplings increasing the risk of an unstable system. A change to a system element can mathematically be described as a change to the transfer function of the element in a control system. This can result in a sufficient shift to the roots of the equation, to cause the system to become unstable emphasising the caution before implementing a change.

In general debugging an unstable system is extremely difficult because of the closed control loop, and normally one has to resort

to mathematical analysis and computer simulations to identify the root cause of the instability. The relevant extract of Viljoen's (2007) presentation is reproduced in appendix A.

Sparrius (2006), states that the behavioural view of a system describes its behaviour over time including which functions are active, their control and timing behaviour, their states and the conditions and events that trigger transitions between states. To facilitate design synthesis, system functions are broken down into states. A "state is a collection of descriptive variables that contain all information about the system." (Sparrius, 2006). A system stays in a state either when the function is active or waiting for an event.

The above discussions provided an overview of the characteristics and properties of a system. From this it can be deduced that design influencing must not only focus on the design item itself but also study the influence of any design change on the system's dynamic behaviour. Even small changes can influence the system's dynamic behaviour and in extreme cases may cause the system to become unstable.

In the next paragraph the salient engineering characteristics for the development of a system (systems engineering) will be discussed.

3.2   Systems Engineering

The National Council on Systems Engineering (INCOSE) web page states that: *"The term systems engineering dates back to Bell Telephone Laboratories in the early 1940s [Schlager, 1956; Hall, 1962; Fagen, 1978]. Fagen [1978] traces the concepts of systems engineering within Bell Labs back to early 1900s and describes major applications of systems engineering during World War II. Hall [1962] asserts that the first attempt to teach systems engineering as we know it today came in 1950 at MIT by Mr. Gilman, Director of Systems Engineering at Bell"* (INCOSE, 2010).

According to INCOSE (2010), the need for a more formal process of system development arose when it was no longer possible to rely on design evolution, using previous designs, to improve and expand upon a system. The existing methods were not sufficient to meet growing demands, and the problem of complex system development is further complicated by the need for the use of different technologies for the various subsystems. To reduce the system development project risks, new methodologies began to develop to address the modern problems of system development. It can be seen that the concept of systems engineering is not new, what is new however, is the formalisation and development of a disciplined process for system development. The development in better more streamlined methodologies is ongoing and is actively pursued by

INCOSE with the following mission statement: "*Our mission is to advance the state of the art and practice of systems engineering in industry, academia, and government by promoting interdisciplinary, scaleable approaches to produce technologically appropriate solutions that meet societal needs.*" (INCOSE, 2010). The evolution of Systems Engineering as it continues to this day comprises development and identification of new methods, and modelling techniques and methods that can aid in better comprehension of engineering systems as they grow more complex (INCOSE, 2010). There are a number of definitions for systems engineering in the literature. The definition by Blanchard (1997), is the most applicable to this research: *"An interdisciplinary collaborative approach to derive, evolve and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability".* INCOSE (2010) states that:"*Systems engineering is a multi-disciplinary effort that involves both the technical effort and technical project management aspects of a project*" (INCOSE 2010).

In the next paragraph the systems engineering process that brings a system into being, will be discussed.

3.3   Systems Engineering Process

The NASA System Engineering Manual (2004), states that the most important reason to apply Systems Engineering is that systems engineering provides the context, discipline, and tools to adequately identify, define, and manage all system requirements in a balanced and orderly manner. Systems engineering provides the disciplines required to produce complete solution concept and system architecture. Systems engineering also provides the discipline and tools to ensure that the resulting system meets all of the requirements that are feasible within specified constraints. In other words following the disciplined systems engineering approach will result in a first-time-right design resulting in reduced project risks.

Currently there are no other engineering or management disciplines that provides for the comprehensive context, or results that can be achieved with the systems engineering process. The need for effective systems engineering becomes more apparent with large, complex system developments, such as weapons and transportation systems. Systems engineering is also important in developing, producing, deploying and supporting of much smaller systems and even consumer products since the discipline lends itself admirably to design optimization within given sets of constraints.

Systems Engineering (SE) is an iterative development and design process described by INCOSE Handbook (2006), INCOSE Handbook (2010), NASA Systems Engineering handbook (NASA 2007), Blanchard (1997) and others. The iterative development and design

processes can run concurrently according to IDA Report R-338 (1988) and Hill (1997). They call this concurrent development process or Concurrent Engineering (CE), (IDA Report R-338, 1988), (Hill, 1997).

3.3.1 Systems Engineering Outputs and Summary

The objective of systems engineering is to produce data packs, (Mil-Std-499B, 1994) with the aim for production and through life support of the system. According to Mil-Std-499B, (1994), a data pack "*is a technical description of an item (product and process) adequate for supporting an acquisition strategy, production, engineering, and logistics support. The description defines the required design configuration and procedures to ensure adequacy of item performance. It consists of all applicable technical data such as drawings, associated lists, specifications, standards, performance requirements, quality assurance provisions, and packaging details*"

The Systems Engineering process has the following outputs:

- **Product data pack.**

- **Production data pack.**

- **Support and Operating data pack.**

The systems engineering process output is ***data*** and not ***hardware***. All hardware models build during the SE process is solely for the verification and qualification of the data packs, (Mil-Std-499B, 1994). An important component of the qualification is product reliability management (Murthy et al, 2008) and reliability growth tests (Mil-Hdk-189, 1981). Design influencing during reliability growth is to test the item until failure, analyse the failure, find the root cause and develop and implement a fix. This process is called Test-Analyse-And-Fix (TAAF) testing, (Mil-Hdk-189, 1981).

The hardware models built during development must be kept under configuration control to enable test and evaluation of modifications as part of through-life engineering support (Mil-Std-1521, 1995), (Saaksvuori et al, 2005).

The systems engineering process described in the literature (INCOSE, 2010), (NASA, 2007), is a good practices sequence of different activities to be performed, in order to develop an effective system according to NAVSO Best Practices (1986). The systems engineering process literature does not stipulate a time or resource criteria on an activity in the systems engineering process. The

deduction that can be made is that the systems engineering process on its own is a static process or guideline. In order to bring a system into being, the systems engineering process also needs a resource and time management process described in the next paragraph.

The salient characteristics and properties of a system and the process to bring a system into being have been discussed. The process so far has been static and in order to develop a system and manage the resources, the relevant characteristics of project management will be discussed in the next paragraph.

3.4 Project Management

Project Management was developed from different fields of application which include construction, engineering and defence. Henry Gantt is credited as a "father" of planning and control techniques by various internet publications in the United States of America (Gantt, 2010). The Project Management Institute (PMI) plays an important role in the project management profession. It has an active global community of more than half a million members distributed in more than 170 countries, including South Africa. It is a leading membership association for the project management profession (PMI website, www.pmi.org, July 2010). Therefore in the project management sphere, PMI and its technical developments play an important role. The PMI has developed the Project Management Body of Knowledge (PMBOK®), which is an internationally recognized standard (IEEE Std 1490, 2003) for fundamentals of project management irrespective of the type of project. The risk management methodology of the PMBOK® is one of the mostly used methods to control risks in projects (INCOSE, 2004). The fourth edition of PMBOK was published in 2008, (PMBOK, 2008).

The PMI states that a project is "*a unique **temporary** endeavour, with a set **beginning** and **end**.*" PMBOK (2008), states that project management is "*the application of knowledge, skills, tools and techniques to a broad range of activities in order to meet the requirements of a particular project*". PMBOK identifies five process groups:

- Initiating

- Planning

- Executing

- Monitoring and Controlling

- Closing.

Processes are described in terms of

- Inputs (documents, plans, etc)

- Tools & Techniques (mechanisms applied to inputs)

- Outputs (documents, products, etc)

There are nine knowledge areas that are applicable across nearly every industry worldwide,(Kerzner, 2009):

- Integration

- Scope

- Time

- Cost

- Quality

- Human resources

- Communications

- Risk management (the subject of this study)

- Procurement

The elements of project success are illustrated in figure 7.
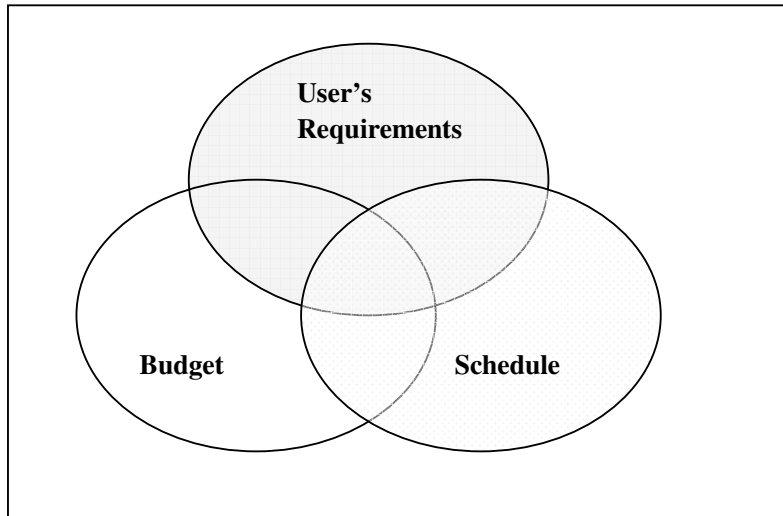
Figure 7: Elements of project success

Source: Coblands Consulting, (1995)

Referring to figure 8, a system cannot be developed using the systems engineering process by itself. It requires project management to coordinate and manage the schedule as well as the consumption of resources to ensure ultimate project success, (Kossiakoff, 2003).
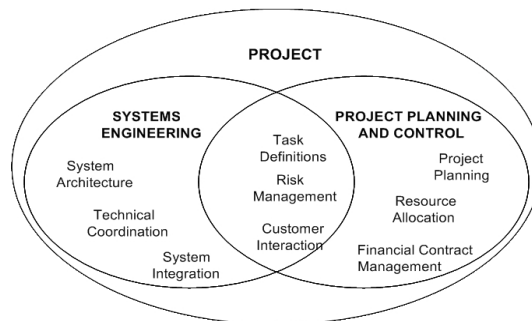
Figure 8: Systems Engineering environment

Source: Kossiakoff, (2003)

From the above discussion, it can therefore be construed that the hierarchy principle is not only applicable to systems but also to the processes that bring the systems into being. No process can run in isolation it is always encompassed inside other processes. As such the process interfaces can have a distinct influence on the process under investigation.

As discussed above, PM manages the resources for a project. To ensure availability of human resources at the right time on the project

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plan, the matrix organisational structure of human resource management will be discussed in the next paragraph.

3.5 Matrix Organisational Structure

The project for the development of multi-component, multi-disciplinary systems can be efficiently managed in a matrix organisational structure.
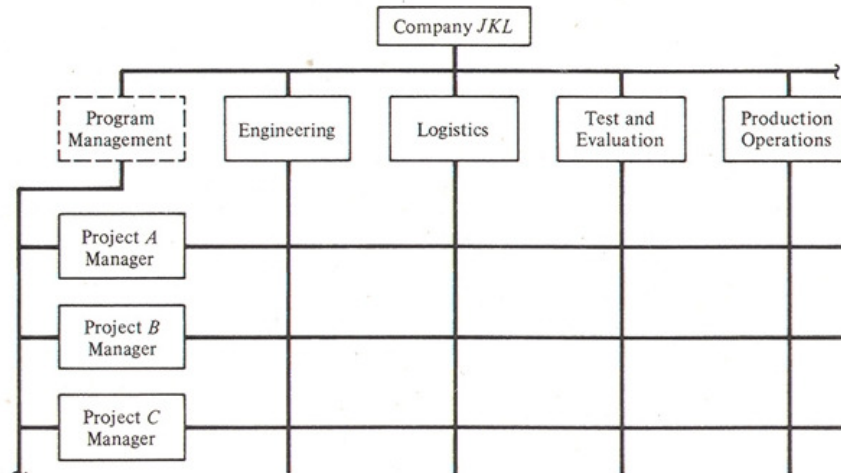
Figure 9: Matrix Organisational Structure

Source: Blanchard, (1998)

The Matrix organisational structure indicated in figure 9, is a two dimensional structure with project lines and functional capability lines generally referred to as facilities. This structure is the preferred organisational structure for the smaller system development companies since it allows efficient sharing of scarce skilled resources between different projects, (Blanchard, 1998).

According to Guzman, (2011), the matrix organizational structure divides management authority both by functional area and by project. In a matrix structure, each employee answers to two immediate supervisors - a functional supervisor and a project supervisor. The functional supervisor focuses on hiring, training and managing employees in their field, while project supervisors can focus on achieving the goals of their specific projects or products. He also states that by placing employees in functional areas allows them to specialize in a particular field. Instead of being good at a variety of tasks, specialized employees can excel at tasks in their field of focus, (Guzman, 2011).

According to Bassiouny, (2011), the advantages of the matrix organisational structure are:

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- Allows employees from different departments to come together temporarily to work on special project teams.

- Provides flexibility to respond quickly to a customer need by creating a team of people who devote all their time to a project and then return to their department or join a new project team.

The downside of the Matrix organisational structure for system development is that once the specific subsystem design has been completed, the resources are re-allocated to other projects and are not available anymore to the current project. This can lead to project delays should during integration a problem be experienced and the original design resources are required.

Another downside is that team members are often selected on availability at the time of the project (Starbek et al, 2002). It is very difficult to compose an optimal team for a specific design project task in a multi-project facility environment. In the smaller companies specialist skilled resources are scarce and in demand by other projects running in the company. This may impact on the selection of an optimal team not only from a technical perspective but also from a human relations aspect and may result in reduced team cohesion, (Kim et al, 2008). The reduced design team cohesion can only be partially countered by a structured design methodology to be further discussed in chapter 8.

The next paragraph will discuss design influencing and the structuring of a design team.

3.6 Design Influencing

The primary focus of this research is design influencing. Design influencing can be viewed as design improvement proposals evaluated in the context of the project's value system.

From the previous discussions it can be seen that a process always functions within another process, and that the other process can have a distinct influence on the original process's performance. The objective of design influencing is to accelerate design optimisation with the aim to drive the design to maturity. The earlier this is addressed in the design process, the lower the cost impact of a design change, (Wessels et al, 1998). Buede (2000) states that design influencing is a process to improve the future status of the product, and one that culminates in the allocation of resources to affect the chosen change. The most commonly allocated resources are human, material and time (Buede 2000).

Design influencing can be made more objective and repeatable by the application of influence diagrams and decision trees (Buede,

(2000). INTELLECT, (2003), further refines design influencing by applying success frame and failure frame considerations to a design.

Design influencing has the connotation of design change or design amendment with the objective to develop a better product. Design influencing cannot be done in isolation as can be seen from previous discussions. A change of the characteristics of a component of a system may also influence the emergent properties and the dynamics of the system in a multi-level hierarchy. The problem is further exacerbated in a concurrent systems engineering development environment. This will be further discussed in chapter 7.

One of the objectives of this research is to optimise design influencing. The design process is a multi-facetted process and is difficult to model, (INCOSE, 2010). Since design is a process for satisfying requirements. Requirements set out what the design must do. This may be functional requirements to describe a service or function or may be non-functional requirements or constraints placed on the design (Sommerville 1996).

Before design influencing can be considered in detail, and a model developed, it is necessary to have a clear perspective of the most basic requirements of a design. A good design must, amongst other factors, function properly within its design parameters and environments and be cost effective. These environments are external influences and are at best predictions that can't be controlled by the designer. To ensure that a design always behaves in a controlled and orderly fashion the designer must also consider the design's behaviour for out of specification conditions. A good example would be a software module processing the data from an external sensor. If the sensor provides data that is erratic and/or out of specification, the software must behave in an orderly manner and must not hang-up, but elevate the condition to the next system level.

Therefore, a good design team must not only focus on the technical requirements for a design but also on the constraints and external conditions which are inherently imposed on the design. This requires two different and almost opposing mindsets which are very difficult to vest in the design team alone.

The studies by Kim et al, (2008) and Kuhn et al, (2006) found that teams that developed integrative conflict management styles made more effective decisions than teams that utilized confrontation and avoidance styles. They also found that teams that never developed a stable style were less effective than teams with integrative styles. Also Kim et al, (2008), found that cross-functional cooperation between teams in new product development had a positive impact on product development performance. These studies also found that work groups comprised of people with opposing mindsets produce better results. A topic under review by this type of work group will be

investigated more thoroughly than would be the case for a group with a homogeneous mindset (Kim et al, 2008), (Kuhn et al, 2006).

Optimising a development team's effectiveness can be approached in a DSR setting by dividing the development teams into two groups addressing different aspects of the design process. One group to focus on the functional requirements and another group must focus on the non-functional requirements.

To achieve the functional requirements, the design team must focus on all aspects design success. The mindset of the team focussing on compliance with the functional requirements is therefore in the design success domain.

To address the non-functional requirements, the design team must focus on how the design can fail and how it must behave under those conditions to achieve the requirements. The mindset of the team focussing on the non-functional requirements can therefore be said to be in the failure domain.

Such a division would lead to a Success Domain (SD) and Failure Domain (FD) team. The SD design team would then focus on the functional requirements whilst the FD design team would focus on the non-functional requirements. However, in practice, the SD and FD teams already exist in most Systems Engineering development environments. The SD team is comprised of those team members responsible for the functional and detailed designs of the system, whereas, the FD team is made up of those members of the team responsible for the Reliability and Logistics Engineering aspects of the design.

Applying these principles and improving team interaction and effectiveness, the design teams are divided into two groups with opposing mindsets:

- A system/subsystem development team, referred to as the Success Domain (SD) team.

- A logistics engineering development team referred to as the Failure Domain (FD) team.

A systems engineer heads each team. One systems engineer was responsible for the development and architecture of the system and the other team was responsible for the reliability and logistics system engineering tasks as well as the subsequent development of the logistics products.

This will create a constructive conflict environment and it is now possible to develop a model to study the interaction between the two domains.
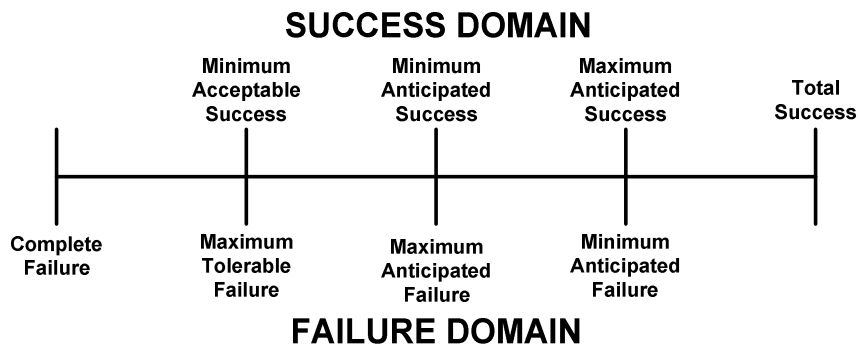
3.6.1 Success Domain Team (SD)

The "***Success Domain***" design team must strive for design success. In other words the mindset of the SD team is: "*what is the minimum acceptable success?*" The mind-set of the SD team comprising systems engineering, subsystem development teams and design engineers are therefore set in the "***Success Domain***".

This team's objective is to get the system, subsystems and associated software working in compliance with the requirements and development specifications.

3.6.2 Failure Domain Team (FD)

The "***Failure Domain***" team must identify design weaknesses. In other words the mindset of the FD team is: "*what is the maximum tolerable failure and what are the weaknesses in the design?*" The mind-set of the FD team is failure mitigation of the design. The whole objective is to analyse the system, subsystems architecture and designs to determine what makes them fail and the maximum tolerable failure.

The Success/Failure domain concept is shown in the figure 10:

SUCCESS DOMAIN

Minimum Acceptable Success	Minimum Anticipated Success	Maximum Anticipated Success	Total Success

Complete Failure	Maximum Tolerable Failure	Maximum Anticipated Failure	Minimum Anticipated Failure

FAILURE DOMAIN

Figure 10: Success/Failure domain concept

Source: Reliability Practitioner's Guide, (2003)

Part of the FD analysis is also to evaluate system behaviour when external conditions are outside specification, in order to ensure an orderly and safe system performance under failure conditions. This will ensure a more robust and safe design. Logistics systems engineering also evaluate designs for Testability, Reliability, Affordability, Maintainability and Produceability (TRAMP) requirements.

Applying the Success/Failure domain concept to the systems engineering process, (INCOSE, 2010), the design influencing

model shown in figure 11 can be developed. This model illustrates the interaction between the systems engineering and logistics engineering processes.

The outcomes of the FD/SD domain analyses are used for design influencing shown in the figure 11:
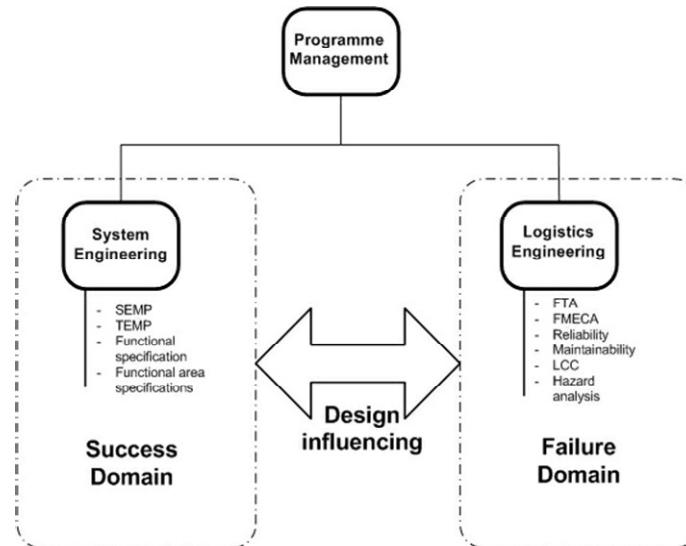
Figure 11: Design influencing model

The design influencing model in figure 11 systems engineering team (SD team) focus on design success by ensuring design functional specification compliance using the established systems engineering processes described in INCOSE (2010).

The logistics engineering team (FD team) analyse the design from a non conformance perspective and the severity and impact on the system using the logistics engineering processes, (Mil-Std-1369A (1988).

Although under the Logistics Engineering umbrella, the FD teams are responsible for design analyses. Logistics Engineers specify the logistic and production products requirements which in turn are developed using a similar SD-FD design influencing process.

The processes discussed above are static in the sense that the processes have no schedule time constraints and have not been considered in a project management environment. Kossiakoff (2003), has shown that a system can only be developed in a project management environment, since project management provides the time function (schedule) to the system development project.

Placing a project management time function on the Success Domain (SD)-Failure Domain (FD) requirements and constraints, a dynamic design influencing model can now be developed shown in figure 12. This model makes the static design influencing processes illustrated in figures 10 and 11 dynamic. The model in figure 12 shows the iterative design influencing process between the success and failure domains.

Figure 12 shows the iterative design influencing between the SD and FD teams. The objective of both teams is a successful compliant design.
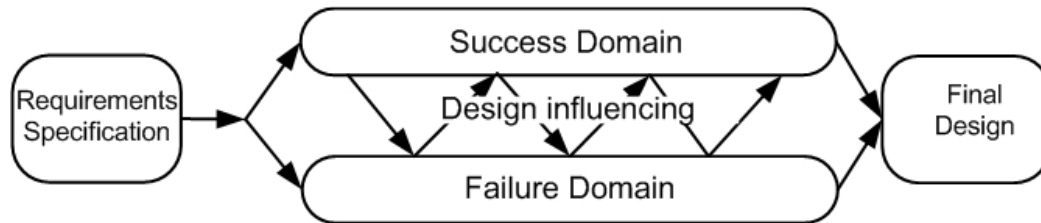
Figure 12: Interaction between the SD and FD teams

3.6.3   Project Management Team (PM)

The project management must satisfy the requirements of the project stakeholders (PMBOK, 2008). Therefore the primary development team objectives others are:

- Successful project

- Satisfied client

- Satisfied company Management

For the development of an anti-tank weapons system, the systems engineering process must function within a project management environment, to manage the consumption of resources to ensure project success.

The PM team is responsible for ensuring that the project is completed according to the contract, within cost and schedule. To achieve this, the project management team must manage the key systems engineering interfaces, (INCOSE, 2010).

Superficially the SD-FD teams and the PM team's objectives appear similar in that both strive for project success; they are in fact distinctly different. SD-FD teams are product focussed and their performance is measured in terms of design success and

compliance. The PM team on the other hand is business model focussed and their performance is measured in terms of company business success (PMBOK, 2008).

3.7   Chapter Summary

In this chapter the main characteristics of a system were discussed. An overview was given of the systems engineering process, required to bring the system into being and the project management environment within which the systems engineering process must function. The matrix organisational structure advantages and disadvantages in the context of a complex system development environment were discussed. A model for design influencing was proposed providing a constructive conflict environment for efficient design optimisation.

The **Success Domain (SD) - Failure Domain (FD)** model was introduced as part of exploratory research in a DSR setting, with the objective of optimising design influencing. Applying the project management time resource function to the model, results in the dynamic design influencing model shown in figure 12. This model will be further expanded and discussed in chapter 7 as part of the case-study root cause analysis.

It was also shown that no process can function in isolation, and that the interactions with other processes must be taken into account when analysing a process. In the system development environment, the systems engineering process interfaces with the project management process and the facility management process. These processes in turn function within the company business management processes. All these processes have a distinct influence on the behaviour and performance of the systems engineering process under investigation and must be taken into account.

The research question: "*Can models be established to depict the success/failure domain interactions in a dynamic project management environment?*" has been shown theoretically feasible. A case-study for the development of an anti-tank weapons system will be used to confirm this model in practice. The development of the anti-tank weapons system will provide a good testing ground for the model since this system consists of multiple subsystems and components applying a broad spectrum of engineering disciplines.

The defence industry worldwide is a specialised industry and with its own terminology. Specifically for the benefit of the non-defence industry reader, an introduction to case-study has been provided. In the next chapter an introduction to anti-tank armour and the case-study background will be discussed to provide a better perspective of

the constraints and processes within which the development project
of the anti-tank weapons system had to function.

"The arms industry is a global industry and business which manufactures and sells weapons and military technology and equipment. It comprises government and commercial industry involved in research, development, production, and service of military material, equipment and facilities."
Wikipedia (2011)
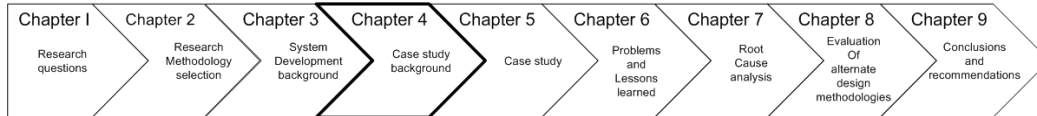
Background of Armour and Anti-Tank Weapons Systems
Introduction to Anti-Tank Missile systems
User requirements background
Ingwe missile description
Top-level User Requirements statement
Primary constraints invoked by client
Contract overview
Project management model

In this chapter the researcher provides an introduction and management background to the case-study.

Chapter 4   BACKGROUND TO THE CASE-STUDY

In the previous chapter, the relevant characteristics of a system, the systems engineering process and the management process within which the systems engineering process functions were discussed.

Exploratory and Narrative Inquiry research methodologies will be applied to the data obtained from the case-study. This will enable the observation of the symptoms of underlying problems. DSR will provide the deeper insight and understanding, required for the research question to allow the development of models, for the success/failure domain development teams' interaction with project management. DSR methodology will provide the means for achieving the research objective of optimising design influencing.

DSR will also facilitate obtaining an answer to the research question to determine the impact of a design change in a system hierarchy discussed in chapter 2. In order to address the research objective to optimise design influencing, as well as evaluate the impact of design change in a concurrent engineering development environment, a case-study for the development of a third generation anti-tank weapons system has been selected.

In this chapter the background of the system and development environment that will be used for the case-study, will be discussed in order to provide a better insight into the case-study for the upgrade of the ZT3 Anti-Tank Weapons System. This will provide better understanding and appreciation of the problems experienced on the development project.

4.1 Purpose and Outline of the Chapter

The purpose of this chapter is to provide background to anti-tank weapons systems, in order to illustrate the multi-discipline technology and complexity for the development of a third generation anti-tank system. A third generation anti-tank weapons system is a good example of a multi-disciplinary, multi-component system in a multi-hierarchical system level structure. The case-study will provide the basis for the research objectives discussed in chapter 1.

This chapter then proceeds to provide background to the procurement, user requirements and high-level contractual requirements. An overview of the management and infrastructure of the contractor is also provided.

The contractor has very well established infrastructures for the development of complex multi-discipline systems and is equipped with the latest information systems and tools. This background should enable the reader to objectively evaluate the case-study and problems encountered.

The objectives of the case-study are:

- Evaluate the concurrent engineering IPS development model on a full scale development project for a complex multi-disciplinary system applying the design influencing model.

- Evaluate the effectiveness of the SD-FD design influencing model.

- Provide data to facilitate identification and quantification of any problems experienced on the project.

- Provide detailed data to enable Root Cause analysis for any problems experienced.

4.2 Background of Armour and Anti-Tank Weapons Systems

This is a case-study of a fully-fledged development project for a complex multi-disciplinary system, inclusive of the associated logistic system, required to provide through-life support for the newly developed system. Detail PRACA (Problem Reporting and Corrective Action) data will be collected for evaluation of the systems engineering process, as well as the development model effectiveness within a project management environment. The author has been involved with this project from day one until the system was finally and successfully put into production and operational use. The project took 3 years to completion.
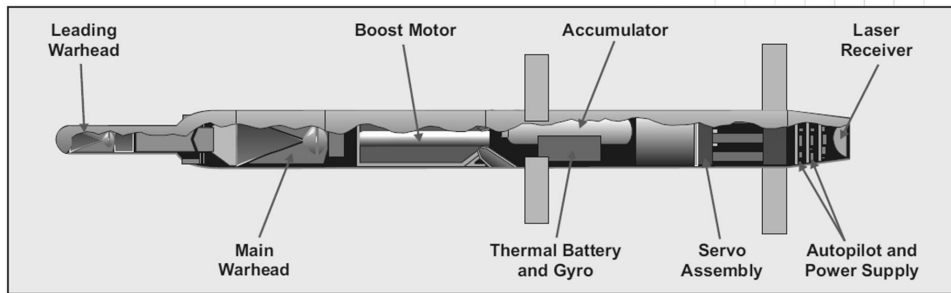
The PRACA data will be analyzed, classified and quantified using the Narrative Inquiry research method. DSR will then be used to provide a better insight and understanding of the analysis results and finding of a solution to the phenomena observed, (Venable et al, 1999) and (Gero et al, 2006).

The system to be discussed for the case-study represents an extensive upgrade to an already existing system in the client's inventory, with many subsystems and software modules being totally new developments. Generally no system development project starts with a zero baseline. Existing system/s and components are generally re-deployed as building blocks for a new developed system configuration, primarily to reduce the cost, development schedule and technical risks (Tomaiko, 2008). For the weapons system development project used in the case-study, certain existing components of the original system were retained but mostly were extensively modified or upgraded. This was motivated particularly from the lessons learned during the operational deployment of more than 10 years of the existing system.

Although this system is equipped with a target auto tracker, it is not a fully-fledged "*Fire-and-Forget*", (Hogg 1996), system, and requires limited human control until the target is destroyed. The design and ergonomics therefore must be such that the workload and human errors are to a large extent minimised. This is also a primary safety requirement of the system. The system description provided in the company marketing brochure is shown in figure 13. More details can be found in reference: Denel Dynamics Ingwe Missile brochure, (2009).
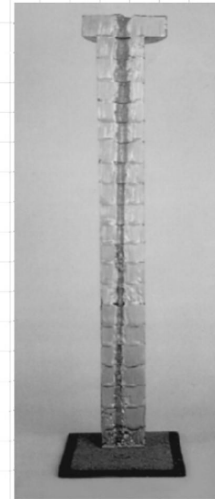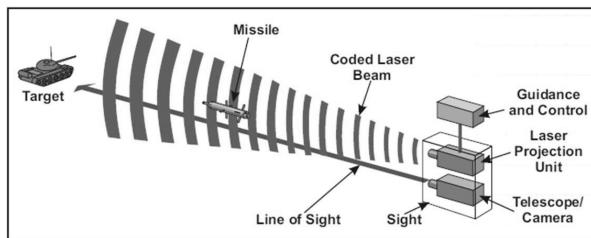
Figure 13: Anti-Tank Weapons System

Source: Denel Dynamics Ingwe Missile brochure, (2009)

This case-study has been compiled from the author's extensive diary of events during the approximately three-year project. As such this research may be categorized as Design Science Research (DSR) in a case-study setting, (Venable et al, 1999) and (Livari et al, 2009). Due to company confidentiality reasons, technical information and product specific data have been limited to what is available in the public domain such as the Internet or marketing brochures. These sources have been extensively referenced where applicable.

4.3   Scope of the Case-study

The case-study will provide the platform to study the optimisation of design influencing by dividing the design teams into two different

mind-set groups and to evaluate the impact of design changes in terms of cost and schedule overruns in a concurrent engineering development environment.

This case-study is extensive as it covers a fully-fledged multi-discipline complex weapon system development complete with the logistics package from day one until the final handover to the client. The prime objective of this research is to evaluate in practice in a DSR research setting, the effectiveness of the proposed design influencing model and the impact of design changes on the project. With this in mind and in order to keep the volume of the research work acceptable and not to lose focus of the primary objective of this research, the project management aspects of the project have been excluded except for areas of conflict between the systems engineering process and project management. The focus for this case-study will therefore primarily be on the systems engineering and design process and be limited to the research objectives.

4.4   Introduction to Anti-Tank Missile Systems

Armour is not new to man. History shows that since the early days, armour has been used in warfare. Soldiers used shields to protect themselves against enemy swords, spears and arrows. As the technology developed, the weapons and armour became more mobile and sophisticated. The Egyptians and Romans used wooden horse drawn chariots (carts) as armoured fighting vehicles. With the arrival of gunpowder, the armour changed from wood to leather to steel. Today we have the modern battle tank in place of the chariot, and high-explosive ammunition in place of the swords, spears, arrows and catapults.

Today, modern armour is highly mobile and has devastating firepower over long distances. Because of its mobility and firepower, it became more and more difficult to destroy modern armour with rockets and conventional guns. Therefore, anti-tank guided rocket (missile) systems were developed. With guided missiles, moving targets can be destroyed over long distances. (Hogg, 1996).

4.5   Evolution of Anti-Tank Weapons Systems

This paragraph discusses the evolution of the anti-tank weapons systems and highlights the complexity and multi-disciplinary characteristics of these systems.

4.5.1   First Generation Anti-Tank Missile Systems

According to Hogg (1996) modern tanks originated during WWI (1914) and immediately after its apparent successful introduction into warfare, anti-tank weapons were developed. Modern anti-tank weapons use a guided missile, since it is highly manoeuvrable and relatively easy to launch and very effective against armour.

In a military situation, the operator identifies a target and launches a missile. Once the missile is launched, two thin wires are dragged out behind the missile and a light source illuminates in the rear end of the missile. The two thin wires form the communications link between the missile and guidance unit whilst the light source indicates the position of the missile in flight to the operator. The operator tracks the target through his optical sight. The operator has to steer the missile using a joystick towards a target that can be stationary or moving. The light source at the rear of the missile indicates the present position of the missile. The operator controls the missile by moving the joystick according to where he wants the missile in relation to the target. When the operator moves the joystick, the joystick generates electrical control signals that are transmitted to the guidance unit. The guidance unit processes the data from the joystick, generates the control signals and transmits the control signals to the missile in flight via the two thin wires. This is referred to as Manual Command to Line of Sight (MCLOS), (Hogg, 1996). The above discussion illustrates system complexity.

Despite being relatively cheap and portable, the main disadvantages of first generation anti-tank missile systems are:

- High operator workload. The operator must track both the target and missile.

- Expensive training. The operators must be well trained and can only train with real missiles.

- Limited range of approximately 2000 m due to the wire link.

- A second missile cannot be launched whilst the first missile is in flight.

- The disadvantage is that the operator must remain stationary and in view of the target during the flight time of the missile.

- This makes the operator vulnerable while guiding the missile.

4.5.2 Second Generation Anti-Tank Missile Systems

In this case the operator again identifies a target and launches a missile. Once the missile is launched, two thin wires are dragged out behind the missile for communication between the missile and the guidance unit. Some systems make use of an optical data link instead of wires for communication between the missile and the guidance unit. Immediately after launch, an infra-red light source illuminates in the rear end of the missile. The infra-red light source indicates the position of the missile in flight. A goniometer that is sensitive to infra-red light determines the position of the missile in flight, relative to the operator's line of sight. The goniometer sends this data to the guidance unit. The guidance unit processes this data and generates control signals for the control of the missile. Control signals are transmitted to the missile in flight via the two wires or via an optical data link. The operator uses a control stick (joystick) to control his line of sight as he tracks a moving target. The goniometer reference is the same as the operator's aiming point. This illustrates the complexity of the man-machine interface and precise interworking of electronics, mechanics, and aero dynamics.

As the line of sight changes, so does the infra-red light source in relation to the window of the goniometer. The guidance unit controls the missile to fly on the line of sight. This is referred to as Semi-Automatic Command to Line of Sight (SACLOS), source: SACLOS, (Hogg, 1996).

The advantages of the second-generation anti-tank systems are:

- Minimum operator interface.

- Training is relatively cheap. Simulators can be used to train operators.

- Long range approximately 4000 m

- Can be carried on a variety of vehicles, for example helicopters and infantry fighting vehicles

The Disadvantages however are:

- Can launch only one missile at a time

- The operator must remain stationary during the missile's flight.

- The operator is vulnerable while the missile is in flight

- Interference to the operator's line of sight due to light, water or terrain.

4.5.3   Third Generation Anti-Tank Missile Systems

Third-generation anti-tank missile systems are primarily automated second-generation anti-tank missile systems of the "fire-and-forget" type. Once the target is identified the missile needs no further guidance during flight. The missiles are "beam riders" and the systems are equipped with auto trackers. These systems also have crossfire capabilities allowing multiple targets to be engaged. The fire-and-forget missiles are more subject to electronic countermeasures than MCLOS and SACLOS missiles. Modern anti-tank guided missiles (ATGMs) have shaped-charge high explosive anti-tank (HEAT) warheads, designed specifically for penetrating armour. A counter measure that is used on tanks is to use explosive reactive armour (ERA). The Tandem-charge missiles attempt to defeat ERA protected armour. The small initial charge sets off the ERA while the follow up main charge attempts to penetrate the main armour source: Anti-tank Guided Missiles, (Hogg, 1996).

The above paragraphs provided a brief overview of the evolution of anti-tank missile systems. Hogg (1996) deals extensively with the subject and is recommended for further reading.

The South African National Defence Force (SANDF) identified a need to upgrade their existing 2nd generation anti-tank weapon system (ZT3A1) to a third generation system.

4.6   User Requirements Background

Anti-tank weapons forms part of the South African National Defence Force (SANDF) army's armour formation, (source: SA Army Armour Formation website, March 2009).

4.6.1   Existing Anti-Tank Armoured Vehicle

The South African National Defence force (SANDF) has operated the ZT3A1 anti-tank missile system very successfully for a number of years, refer to figure 14.
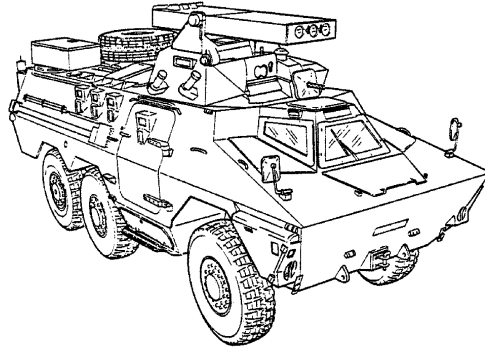
Figure 14: ZT3A1 Anti-tank Missile System

Source SA Army Vehicles website (March 2009)

This system was becoming obsolete and difficult to operate and maintain. The system was primarily an analogue control system with interaction between many critical functions and tasks adding to operator work load and task complexity. The main disadvantage of the system was that it needed well-trained and skilled operators to successfully apply the system. The system did not have automatic target tracking to ensure fully automatic missile guidance after target lock-on by the operator, an essential feature particularly against moving targets. The missile range and penetration, particularly against reactive armour, made it less effective against modern tanks. The system had no night and cross fire capability. Crossfire is the ability of engaging multiple targets by a battery of ZT3s by the coding of laser beams and missiles so that a missile in flight could not accidentally jump from one beam to the other.

The ZT3A1 has an extensive and well-established integrated logistic system consisting of:

- Ratel missile platform support infrastructure

- Ratel Turret support infrastructure

- Missile weapon system support infrastructure

- Maintenance and recovery vehicles (MRVs)

- Training system

This integrated logistic system interfaces with the user's standard support systems and tactical communications network.

The above discussion provides the contractual framework for the project.

4.7 Ingwe Missile Description

A critical component for any successful anti-tank weapons system is the missile. The SADNF already had an effective air-to-ground missile (Ingwe) complying with all the new anti-tank requirements in their inventory. In the drive for standardisation, this missile was selected for the new anti-tank weapon system.

The primary function of any weapons system is to destroy an enemy target. The missile must be designed and controlled by the weapons platform to be able to perform this function. The Ingwe missile is a modern South African developed multi-role laser guided anti-tank guided missile (ATGM) manufactured by Denel Aerospace Systems. The missile was designed to be employed in various roles, either by infantry or as a vehicle or helicopter mounted system for targets at ranges from 250m to 5,000m and is fitted with a tandem shaped charge warhead, able to penetrate ERA protected armour up to 1000mm thick. Ingwe is also fitted with a dual redundant, standoff fuse, optimizing warhead penetration against pre-confirmed targets. The missile's on board software is able to detect the launch platform and download the correct software for the application during launch time. This feature enables the use of a single missile across all launch platforms. The missiles can be fired on crossing flight paths, at different targets on the battlefield without guidance disruptions. The missile can also be used at night by means of thermal imagers, integrated with the sight, source: Denel Dynamics Ingwe Missile brochure, 2009.
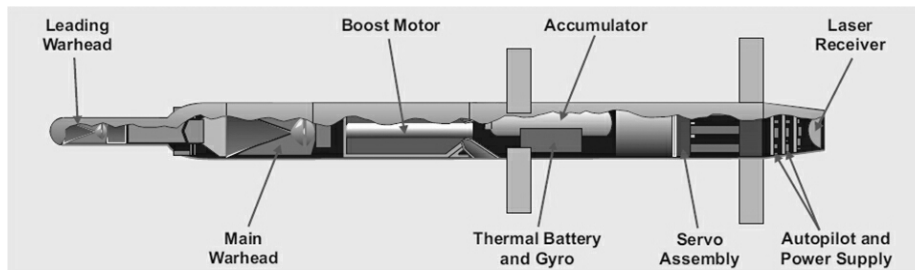
Figure 15: Ingwe Missile cut-away

Source: Denel Dynamics Ingwe Missile brochure, 2009

4.8 User Requirements

Discussed earlier, the client identified a need for a 3rd generation anti-tank weapons system since its existing anti-tank weapons system which was becoming obsolete. To this effect, the client in its aim to modernise their current anti-tank weapons system has prepared a high level User Requirements Statement (URS). The URS specified the requirements for a third generation Missile Products System identified by the acronym NGMPS. To contain costs, the client

decided to upgrade their existing ZTA1 anti-tank inventory to NGMPS level of capability and performance. The URS specified both the functional and non-functional (constraints) requirements. The main requirements can be broken down into:

- Mission requirements

- System requirements

- Interface with other system requirements

- Design and construction requirements

- Missile requirements

- Testability, Reliability, Affordability, Maintainability and Produceability (TRAMP) requirements

- Logistic requirements

- Support system requirements

4.9   Primary Constraints Invoked by the Client

The primary constraints for the development of the new 3rd generation anti-tank weapons system invoked by the user were:

- The use of customer furnished items (CFE)[2] such as the Ratel Anti-Tank armoured vehicle, Ingwe missile and Training System.

- The user emphasized that the silhouette of the upgraded weapons system vehicle must be similar to that of the standard Ratel Mk3 or of the ZT3-A1 Ratel Mk3 to ensure difficulty in distinguishing between the old and the upgraded anti-tank missile systems. This implied that no major modifications to the outside of the armoured vehicle and turret were allowed.

- The use of the existing Ingwe missile in an ordnance standardization drive. The Ingwe missile is already in its inventory and is being successfully deployed by the attack helicopters (AH) and other armed forces.

- Statutory requirements such as International Traffic in Arms Regulations (ITAR, 2011), road ordinance compliance and safety requirements.

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[2] CFE is a non tradable requirement that places a constraint on the system architecture

- Timescale.

- Costs.

4.10 Contract Overview

The contract placed was for the upgrade of the existing:

- Missile system which includes:

    - Upgrade to the existing Ratel missile platform

    - Upgrade to the existing Ratel missile turret

    - Upgrade to the missile weapon system

- Upgrade to the existing ZT3A1 training system

- Upgrade to the existing maintenance recovery vehicle (MRV)

The client included contractual penalty clauses to ensure project performance and schedule. The production contract was excluded from the development contract and would only be placed once the system has been fully qualified and accepted by the client.

4.11 Project Management model

Project management for the weapons system development project consisted of the five project processes (PMBOK 2008) discussed in chapter 3 and applied to the nine knowledge areas identified by Kerzner, (2009).

A project manager with supporting engineering and QA functions headed the customer procurement organisation. A project manager supported by systems engineering, quality assurance, configuration management and procurement headed the contractor organisation.

These two teams formed an Integrated Project team (IPT) for all technical and baseline issues. The IPT met on a regular basis.

Various workgroups with client operational and specialist personnel were formed for detailed client information to facilitate design optimisation e.g. ergonomics, munitions, training, support work groups etc. These groups got together as required.

To manage scope creep, the work groups had to make recommendations to the IPT for final approval.

4.12   Contractor's Management Model

The contractor organisation was structured on the matrix management organization structure where the different facilities were contracted by the project, Blanchard (1998). The contractor has SAP3[®3] implemented as the management information system to manage labour, finance and material resources as well as for configuration management. For requirements traceability, the contractor used DOORS[®4] for traceability of requirements through all the specifications, (DOORS, 2010). Failure reporting and corrective action system (FRACAS) was implemented more broadly as a problem reporting and corrective action system (PRACAS) since all development/design problems, project problems as well as test failures were recorded on this system. This system is also implemented on the contractor's SAP3[®] management information system. Regular project configuration board (PCMB) and failure review board (FRB) meetings were held to approve engineering change proposals and to activate corrective action on the confirmed recorded problems and failures. This PRACAS database was also used for reliability growth evaluation and substantiation during qualification testing. Apart from the comprehensive management information system, the different facilities in the contractor's organisation were equipped with specialist analytical tools such as Relex[®5], Simulink[®6], Creo[®7].

4.13   Introduction to the Case-study Summary

The aim of this chapter is to provide introduce the case-study project as part of the selected research methodologies discussed above and pave the way for achieving the research objectives and answers to the research questions posed in chapter 1.

This chapter has provided a background and overview of the system to be developed, the high-level customer requirements and the contractor's organisation management infrastructure. The risk of scope creep has been abated through a dedicated IPT management forum. In the next chapter, the detail development process of the anti-tank missile weapons system will be discussed.

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[3] SAP is the registered trademark of SAP, Germany, www.sap.com
[4] DOORS[®] is supplied under licence by IBM[®] Rational[®] DOORS[®];
http://www-01.ibm.com/software/awdtools/doors/ (August 2010).
[5] RELEX[®] is supplied under licence by RELEX Software Corporation, 540 Pellis road, Greensburg, PA 15601, USA.
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