A Systems Engineering approach for the deployment of an atmospheric monitoring station

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NORTH-WEST UNIVERSITY
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NOORDWES-UNIVERSITEIT

It all starts here ™

Soli Deo Gloria

Solo Christo

Sola Gratia

Sola Scriptura

Sola Fide

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Abstract

Atmospheric monitoring is a vital part of environmental management. Monitoring temporal changes in atmospheric pollution on a local, regional and global scale is important in order to mitigate adverse effects on health and the environment. Currently there is general agreement that atmospheric pollution should be monitored, however, less emphasis is often placed on what should be achieved and the specific monitoring that should be included. Atmospheric pollution monitoring is often hampered by geographically restricted and site specific effects resulting in inefficient or ineffective information transfer to the local manager. The scientific community in the developed world often underestimate problems associated with the maintenance of comprehensive atmospheric measurement stations in Africa. A holistic approach is needed to optimise atmospheric monitoring according to specifications set out by system design; this includes site selection, site design, maintenance and quality control.

The aim of this dissertation is to apply the Systems Engineering approach to a case study, the Welgegund atmospheric measurement station (WAMS), to offer a holistic view of interaction between different operational systems and the complexity behind their management in order to be informative to students and personnel from a non-engineering background. A knowledge gap exists that links practical industry related sciences such as engineering to more fundamental and theoretical sciences.

In this dissertation the customer need was determined and an operational concept was developed for the WAMS system. The high level goals of the WAMS were derived and stated as applicable to other new as well as established measurement stations. Technical and fundamental requirements such as trained staff for appropriate logistical support and a broad spatial coverage of air quality monitoring were identified. The system boundaries and operational constraints were established for the WAMS, exposing weaknesses and proposing solutions to ensure long term sustainability. Weaknesses include irregular funding periods and retention of expertise (trained students leave academia for industry) whereas a possible solution included overlapping projects and contracts. Functional analysis highlighted the design and establishment process of the WAMS. Physical architectures and interfaces were explored and finally the success of the establishment of the WAMS was evaluated by a reliability block diagram. The reliability of the WAMS system was calculated to be 96.6 %. This agrees well with the percentage data coverage calculated for the gaseous (95.9 %), aerosol (93.4 %) and meteorological (94.6 %) systems (15 min averages). The reliability of the national grid to supply power to the WAMS was found to be the main restrictive component.

It may be a challenge interacting and coordinating projects with different disciplines, branches or sectors outside of a speciality project. This study has bridged the gap between industry related sciences such as engineering to more fundamental and theoretical sciences. A framework has been provided that highlights the techniques of Systems Engineering and provides an understanding for the need and process of atmospheric monitoring.

Keywords: Systems Engineering, atmospheric monitoring, Operational Concept, Functional analysis, Welgegund atmospheric measurement site

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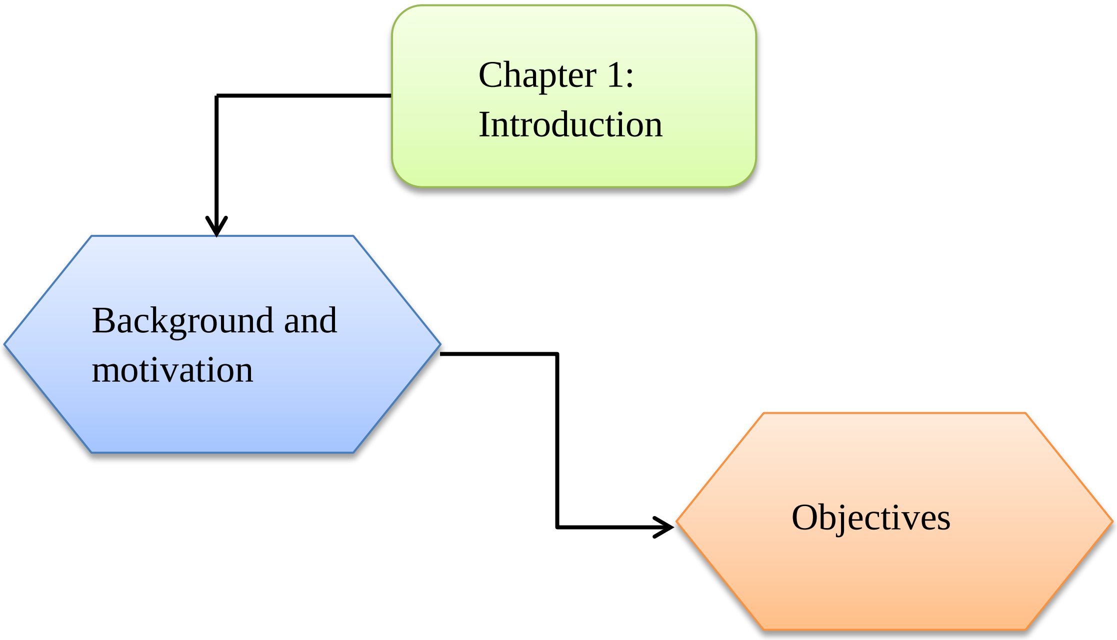
Chapter 1



1. Introduction

In this chapter, the relevance of the current investigation in terms of air pollution, atmospheric monitoring and a systems engineering approach is briefly discussed. Chapter 1 also presents the scientific gap that was identified and the objectives set for this study.

1.1 Background and motivation

Monitoring temporal changes in atmospheric pollution on a local, regional and global scale are of extreme importance in order to mitigate adverse effects on health and the environment, especially long-term effects (Venter et al., 2012). While there is a general agreement that atmospheric pollution must be monitored, less emphasis is often placed on what should be achieved and the specific monitoring that should be included (Laakso et al. 2008). Depending on the nature of the monitoring station, atmospheric pollution should at least be aimed at early detection with optional long-term sustainability. Due to the volatile nature of ownership, funding and the retention of expertise, successful succession may become an obstacle. To minimise complications, learning curve and ease of access to quality data, automation and proper initial establishment are all vital.

Atmospheric pollution monitoring is often hampered by geographically restricted and site specific effects (Usero et al., 2010). Regional data and site-specific data may prove inefficient or ineffective in providing information to the local manager. Atmospheric monitoring is a vital part of environmental management and should include three tasks, i.e. data capture, data analysis and decision making (Petäjä *et al.*, 2013). All environmental issues are dynamic meaning they exhibit both a spatial and a temporal dimension. Ideally, environmental monitoring should be kept on a continuous space and time frame (Ferreira et al., 2000).

As reported by Scholes et al. (2009), problems associated with the maintenance of comprehensive atmospheric measurement stations in Africa are underestimated by the scientific community in the developed world. Atmospheric monitoring station site design and deployment areas have in the past relied on experience, intuition and subjective judgement (Illston et al., 2008). A holistic approach is needed to optimise system design according to specifications with regard to site selection, site design, maintenance and quality control. The approach should be cost effective and deliver quality data, while satisfying social, economic and environmental constraints (Usero et al., 2010).

Seldomly holistic views of interaction between different systems and the complexity behind their management are understood by students and personnel from a non-engineering background (Islam & Islam). As a result it may be challenging interacting and coordinating with different disciplines, branches or sectors outside of their speciality. **A knowledge gap therefore exists that links practical industry related sciences such as engineering to more fundamental and theoretical sciences.**

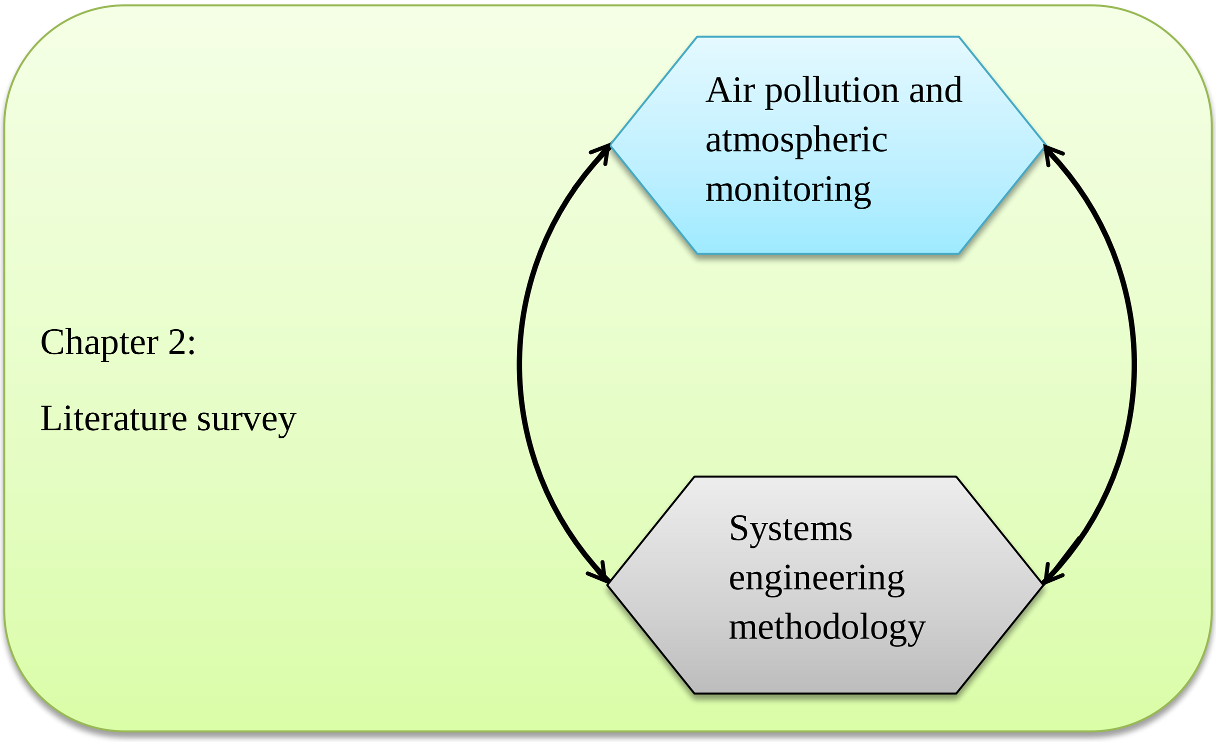
In this study, a Systems Engineering approach is used to systematically describe the process of moving from concept to design, development, implementation and finally testing the project lifecycle process. By using the SE approach, new and established atmospheric monitoring stations could generate quality data that would contribute to the knowledge of atmospheric sciences on a local and especially global scale. The Welgegund Atmospheric Monitoring Station (WAMS) project has been used as a case study. The WAMS is a newly established comprehensive atmospheric monitoring station situated at Welgegund, South Africa (Beukes et al., 2014).

1.2 Objectives

The aim of this dissertation is to apply the Systems Engineering approach to a case study, the WAMS, to offer a holistic view of interaction between different operational systems and the complexity behind their management in order to be informative to students and personnel from a non-engineering background. This will be achieved by:

i. Developing an Operational Concept for the WAMS project indicating typical short, mid and long-term goals applicable to other new, as well as established measurement stations;
ii. Defining the system boundary by investigating possible project weaknesses and proposing solutions;
iii. Investigating the customer need and stakeholders relationships within WAMS;
iv. Performing functional analysis for the design and establishment of WAMS;
v. Exploring the physical architectures and interfaces in the newly established WAMS;
vi. Testing the design by calculating the operational availability of the system.

Chapter 2



2. Introduction

In this chapter, background information for this study is presented with particular reference to air pollution, atmospheric monitoring and the theory of systems engineering. The sources, sinks and impacts of air pollution will be discussed and contextualised with South African legislation. The systems engineering thinking, tools and methods used in chapter three will be discussed.

2.1 Air Pollution

Kampa & Castanas (2008) define air pollution as a change in the natural composition of the atmosphere that is harmful or injurious to human life and the environment. Depending on the severity and cumulative effect, air pollution may disrupt the natural cycles in the atmosphere responsible for weather patterns (e.g. global warming) and chemical reactions (e.g. acid rain) affecting the planetary health (Jacobson, 2002). Many different pollutant species exist in the atmosphere and originate from various sources and chemical transformations, therefore their impact on human health and the environment are diverse (Venter *et al.*, 2012). Physical and chemical properties of these pollutant species determine their impact and must therefore be monitored. Pollutant species my either be in the gaseous or aerosol form (aerosol is a particle or liquid suspended in a gas) and may either be emitted directly into the atmosphere (from natural or anthropogenic source), i.e. primary pollutant, or formed through chemical reactions occurring in the atmosphere, i.e. secondary pollutant (Venter, 2011).

The removal of pollutant species from the atmosphere is crucial. Venter (2011) and references therein describe the removal occurring either through dry or wet deposition. They explain that dry deposition is mainly reliant on the physical properties of the pollutant species and the earth such as particle size, gravity and turbulent mixing. Wet deposition is considered as the main pollution removal mechanism from the atmosphere. In wet deposition, pollutants are dissolved in cloud water and precipitated from the atmosphere.

Atmospheric pollutant species can cause serious health-related problems depending on their physical properties, chemical composition and concentrations. It is a well-known fact that an increase in air pollution is associated with an increase in mortality and hospital admissions (Brunekreef & Holgate:, 2002). The direct and indirect adverse effects caused by atmospheric pollution on human health and the environment demand the measurement and reporting of air quality on a local, regional and global scale (Venter *et al.*, 2012). In Figure 2.1 the difference in air quality of the past century in London can clearly be seen. Air quality is not a problem of the past as many major cities in both developed and developing countries still struggle with mitigation. Similar views to Figure 2.1 A can be seen in 2014 of Johannesburg, Beijing, Paris and many other major cities.

Figure 2.1: In the past century, air quality mitigation practices have contributed significantly to our health and the environment. In Figure 2.1 A (Daily Mail, 2013) the St Pancras Railway

Station is covered by smog in the summer of 1907, while a clear view is visible on the 18th of May 2014 in Figure 2.1 B (Britainfromabove, 2014).

2.2 Atmospheric monitoring

Federal agencies such as the world health organisation have developed air quality standards and guidelines in an attempt to improve the air quality worldwide and protect the public against severe health effects. Although South Africa is currently regarded as a developing country, there are aspects of a developed country, i.e. South Africa is a significant source region of atmospheric pollutants due to biomass burning and the growing economy but have air quality standards that are in line with those of first world countries (Lourens *et al.*, 2012; Venter *et al.*, 2012). The South African legislation makes provision for the identification and declaration of geographical air pollution areas termed Priority Areas. In these areas the local air quality standards are frequently exceeded and require improvement.

Atmospheric monitoring projects may have different deliverables, such as a product, service or result. In this study, the successful deployment of the Welgegund atmospheric measurement station is determined by the product. The product in this case includes quality high resolution data that has been published. Product analysis is an effective process to translate the product descriptions into realistic deliverables. Techniques such as requirement analysis, systems analysis, product breakdown, value engineering and systems engineering may be used in product analysis (PMBOK, 2013). For the purpose of this study, the process of systems engineering will be applied to the knowledge based principles, practices and perspectives of the WAMS and its establishment. The principles include the formal theoretical framework for problem-solving in new situations whereas practices represent operating procedures that are based on experience and accumulated wisdom, in addition perspectives are the future views and directions based on current technological developments (Sage & Rouse, 2009).

Atmospheric aerosol characterisation and trace gas concentration monitoring mostly take place at fixed measurement sites like the Welgegund atmospheric monitoring station (Petäjä *et al.*, 2013). Petaja (2013) explains that this is mostly due to limited resources and the number of measurement sites needed to get a wide spatial coverage not being economically feasible. He states that a transportable trailer could provide descriptive measurement data assisting in the planning of fixed measurements. This was the case concerning the WAMS. A mobile trailer was first employed to assess the atmospheric conditions in a natural and polluted environment in the regional context before being established as a regionally representative long-term measurement station.

Figure 2.2: The Welgegund atmospheric measurement station

2.3 Systems Engineering

Systems engineering may be described in terms of structure, function and purpose but also characterised according to efforts, methods and tools of the life-cycle processes. One discipline within systems engineering is systems management, i.e. the measurement, decision making, and control of life cycle processes. The human dimensions in systems management are associated with sponsors, stakeholders, clients and beneficiaries. Human dimensions also include engineers, technicians, and end users (amongst others), all of which make up "users" of a system. Users are not only end-users, but everyone touching the system (in its strictest definition) throughout its life cycle. – all of which form part of the system-of-systems.

Therefore systems engineering has been defined as a multidimensional trans-disciplinary endeavour (Sage & Rouse, 2009).

There are various ways in which systems may be classified. Misra (2008) identifies two categories of systems, physical and conceptual. Physical systems are tangible while conceptual systems are related to ideas, models, designs, plans, symbols, concepts and hypotheses. These systems are related in the sense that conceptual systems are vital to the functioning of physical systems. Misra further states that many existing systems in industry, i.e. computers and communication, are all artificial although they do interact with natural systems at the same time. Human interaction and functioning with engineering systems may change from system to system and therefore man shall always be considered as an element of the system.

Systems engineering and systems management have in the past been put to practice in many different fields. However, a trans-disciplinary challenge exists, integrating well-known engineering concepts into non-engineering fields. Since smaller endeavours do not have the budget to employ vast amounts of personnel and research, the availability of previous knowledge (in the form of case studies) is vital in order to maximise efficiency and prevent the re-invention of the wheel. As an example, atmospheric monitoring is often initiated by scientists, government officials or managers with little or no knowledge relating to the systems engineering field. Moulding systems thinking into the specific field of study is the first step in awareness, the awareness results into further research and finally a beneficial life-cycle approach. Put to practice in the atmospheric monitoring field: improved physical and managerial functioning when deploying an atmospheric monitoring station is achievable. The use of system sciences when considering the life-cycle approach should adequately plan for limitations and constraints within the project and allow for system expansion both physically and economically.

2.4 Customer need

In the project management body of knowledge (2013) (PMBOK) textbook, the customer need is synonymous with the voice of the customer and entails the critical characteristics of the desired product. The needs of the customer/s are sorted and prioritised, each with realistic goals. Preferably, one need defines one system and one project. The need is typically translated into requirements that describe the lower level "needs". A requirements workshop is often held to determine the required functionality of the system, describing stakeholder goals, motivation and benefits.

Globalisation and increasing competiveness are forcing all branches of industry to react to the demand of individualisation, decreasing costs and increasing customisation (Du *et al.*, 2003). Customisation and personalisation satisfy the customers' personal needs. Although mass customisation has been discussed in literature since the early 1990s, practical implementation of the principles in business can only be found in recent years (Du *et al.*, 2003).The assessment of the customer need is considered to be one of the major factors in product innovation and innovation management. However, few studies have analysed the significance of customer need with regards to managerial problems that exist in the early phases of product development (Kärkkäinen & Elfvengren, 2002).

According to Senge (1990), systems thinking is about seeing the whole instead of separate details, and seeing seeing behavioural characteristics and interrelationships instead of static snapshots. He argues strongly for illustrative ways to uncover and improve the existing mental models of individuals, which are quite often incomplete, and different from each other, to achieve a better common understanding and to facilitate effective learning in organizations (Kärkkäinen & Elfvengren, 2002). This holds true for the customer need as well since the organisation's service to be delivered must be dynamic and flexible to the needs of the customer, i.e. customisation and personalisation. An approach to analyse the needs of a customer may consist of group meetings or personnel interviews to form an extensive, holistic company-level view of development needs (Kärkkäinen & Elfvengren, 2002). Du et al, (2003) explain that in a scenario of customization and personalization, the focus has to be proactive instead of passive analysis. They deem it necessary to understand individual consumers from the designers' side, as well as from the clients' side to provide guidance for consumers to find what they want and to help the clients to explore their preferences through informed choices.

The customer need must be clear to all employees before any further design or operation commences. In the study of Kärkkäinen et al., (2002) interviewees indicated that a lack of resources often resulted in a poor customer need assessment resulting in unclear responsibilities and tasks that required additional clarification. In addition, common problems resulting from the customer need assessment were part of the assessment of future needs determined by the research and development (R&D) co-operation with customers. The solutions to these problems are said to be company-specific due to different company cultures as well as existing product processes and procedures. They argue that companies should promote the importance of customer need assessment for the success of product development, and provide a practical, illustrative way to explain and if necessary, motivate its significance to other stakeholders, beneficiaries, clients etc. in the company.

While customer need patterns characterize customer preferences and are formulated from the customer perspective, functional requirement templates reflect the company's capability and are constructed from the engineering perspective (Kärkkäinen & Elfvengren, 2002). Du et al (2003) specify that accurate product definition and quick response to product customization and personalization are premier competitive advantages for an organisation to maintain its market share and to excel itself among competitors.

2.5 Operational concept

In the operational concept the knowledge and information defining the development and deployment of the system of interest (SOI) are captured. The needs of the clients are captured in functional form and consequently relayed to the functional architecture. Sage and Rouse (2009) indicated the major stakeholders associated with the deployment of an intricate system to be:

- The clients requesting the system;
- The team responsible for management, technical direction and integrity of the system;
- Implementation specialists responsible for successful commissioning of the system.

Data captured within the operational concept provides the information needed when conducting a feasibility study, designing, evaluating a prototype, building and testing the SOI (PMBOK, 2013). Of course, each of these steps may be repeated until the desired outcome is achieved. To design and manage systems effectively, a person should understand the various systems and choose an appropriate concept (Sage & Rouse, 2009). Therefore the greatest need is an adequate conceptualisation of operational systems.

The operational concept may require a high level behavioural model and functional architecture, including all operational processes, procedures, resources and all support systems, in order to indicate that it satisfies the requirements needed to produce a product or accomplish the goals set out by the project sponsors. In Daly (1991) he outlines that the operational concept most often relates to critical thinking about economic development and the environment in the next decade. He states that the operational concept could either be a circular flow or a one-way throughput. The one-way throughput needs two dimensions, its scale and allocation, therefore striking a balance between the efficiently allocated weight of the economy and the scale of the environment is vital. This balance is said to lead to sustainable development. Daly (1991) states that considerable confusion still remains around the meaning of sustainable development, confusing the decision between throughput and circular flow. Throughput signifies a never ending escalating economic growth but with consequences (not sustainable, although desirable), in contrast, circular flow indicates a system of harmony with no consequence, but a limited growth potential. In every operational concept, the systems thinking should be applied to manage the ideas of throughput and circular flow and a reach a concept that balances these ideas sustainably (Daly, 1991).

2.6 Operational constraints

The constraints associated with the operations at the SOI are defined as those that limit the practical functionality and hinder the long term sustainability. For example, the operational technology employed may be considered a constraint since all technologies have limitations such as the measurement resolution and performance deviation(s). The output from the employed technology may be precise but not necessarily accurate or accurate but not necessarily precise (PMBOK, 2013). Although financial constraints mostly govern long-term sustainability, several other limitations exist such as managerial hurdles, asset depreciation, customer need and system flexibility.

Operational constraints have two major classifications, the philosophy of on-going improvements and a generic approach for investigating, analysing and creating solutions to problems (Rahman, 1998). Goldratt (1988) stated that every system must have at least one constraint, if this were not the case unlimited profit would be a reality. However, the constraints of an organisation represent opportunities for improvement, increasing a systems' performance. Rahman (1998) describes five steps for continuous improvement. These steps are to identify the system constraints, decide how to exploit the system constraints, subordinate everything else, elevate the system constraints and when surpassed, repeat. The implementation of these five steps are said to quickly yield substantial improvements in operations and profits (Noreen *et al.*, 1995). However, these constraints are mostly of diverse nature and policy related constraints may be more difficult to evaluate and span multiple functional areas as compared to physical constraints. Constraints are used in cost-effectiveness trade-offs and can also guide designs to result in a system that has been optimised in a multi-dimensional space of constraints.

When dealing with operational constraints, Goldratt suggests three decisions have to be made: Decide what to change, decide when to change to and decide how to cause the change. These are cause and effect principals. To gauge the success of the organisation in relation to the constraints, performance measures are used. These performance measures may include the throughput, inventory and operating expense of the system or organisation (Rahman, 1998). Therefore performance measurements are different from traditional cost accounting. Constraints are also legislative in nature, "design for" and other effectiveness constraints that must all address performance goals (for example, safety, security etc.). Typically, performance measures are defined for optimisation and design dependent parameters are adjusted within a constrained space.

2.7 Organisational system boundaries

Projects like the SOI materialize in a larger environment than the project itself. Understanding the broader context ensures that duties are performed in alignment with the goals and vision of the organisation. In this section the organisational influences affecting the execution of the project and management thereof are addressed. An organisations culture, style and structure determine how its projects are performed (PMBOK, 2013). In the case of the SOI the project may be influenced by more than one organisation including international collaboration partners, therefore sharing common visions, mission and expectations. Policies and regulations as well as the operating environment should be fixed if prior knowledge exists. Knowledge transfer and capacity building between collaborating partners is vital as not to limit the organisations’ functionality and to facilitate better decision making.

Organisational boundaries are influenced by various processes and procedures. These include:

- Planning e.g. design, standards, policies and audits;
- Executing, monitoring and controlling;
- Operational environment, political climate, human resources;

- Closing of the project.

Research and development (R&D) are fundamental to the long-term success of many organisations. Sage and Rouse (2009) indicate that successful R&D depends on at least two organisational properties, creativity of personnel and effective organisational decision making. If the system is stable within a particular segment or stage of development, the next level may be initiated. In this dissertation the focus is on effective organisational decision making.

2.8 Functional analysis

Functional analysis is performed as a critical element of the design process. In the design process, typical steps include requirements definition and analysis, functional analysis, physical or resource definition and operational analysis (Sage & Rouse, 2009). Although each one of these require a comprehensive description in their own right, in this section their high level amalgamation will all be given under the functional analysis umbrella. Functional analysis addresses the activities (inputs, outputs, constraints and enablers) that the system must perform to achieve the desired outputs. Additional elements are the flow of data between functions, the control logic and processing instructions. Functional analysis is therefore depicted in diagrammatic style to capture these concepts (Sage & Rouse, 2009).

System engineers use functional analysis to optimise the functional requirements of the system, to visualise the functions of the physical components and to guarantee that no unnecessary components exist within the system (Viola *et al.*, 2012). In chapter three, the functional analysis presented relates to the conceptual design of the SOI in the form of a functional tree. Once the customer need, operational concept and various constraints and boundaries have been defined, the system requirements can be established. Through the understanding of the system requirements the conceptual design process develops resulting in the functional analysis. Viola et al (2012) indicate that functional analysis has in the past been used in different ways, for example to decompose the functional requirements and focus only on a single task i.e. functional tree or by considering functional analysis as the systematic process of identifying, describing and relating the functions to the system.

The functional tree represents the system by means of the functional view (“what does it do?”) alternative to the more common physical view (“what is it?”) (Viola *et al.*, 2012).

Although both views offer a fundamental approach to analyse complex systems it is up to the need of the organisation to determine the level of detail and analysis. The abstract view, typical of the functional tree, fosters the search of alternative solutions, thus avoiding biased choices. The functional view is absolutely coherent with the systems engineering view, which looks at the system as the integration of various elements. Since the focus of the mini-dissertation is on a systems engineering approach, the use of functional analysis as such a comprehensive tool, will be limited. Functional analysis falls within the System architecture definition. In the following section the Physical- implementation architectures and interfaces will be discussed.

2.9 Physical implementation architectures and interfaces

System engineering aims at finding integrated solutions to provide products, services and processes to satisfy clients.. The term architecture describes a static composition of functional elements (building blocks) and their interrelationships. System behaviour uses these functional blocks as abstracted, logical units to function as logical resources of the system. Logical resources are then later converted to physical resources. Functional architecture is not only subjective to the constraints of the enterprise but must adhere to regulations set out by other stakeholders, such as government. Functional architecture is generally transformed to produce the physical architecture of the major systems for subsequent implementation (Sage & Rouse, 2009).

A variety of tools and disciplines are needed to successfully run a project. However, the principles of systems engineering have clustered these theories and tools in a manner that would satisfy a complex system such as our SOI. Sage and Rouse (2009) grouped these clustered disciplines as follows:

- Systems Engineering procedures, standards and checklists;
- Technical and engineering;
- Economic and financial;
- Management and business-aspects;
- Behavioural sciences and organisation theory;

- Mathematics and statistical tools for analysis.

A manager should have knowledge in many areas but above all, in that of systems and their interaction.

In order to complete the system architecture, the definition of the system budgets (mass, electric power, thermal power budgets, etc.) has to be carried out. However this task can be fulfilled only after the system modes of operation have been established. The modes of operation are part of the mission definition and can in their turn be set up only after the subsystems and their equipment have been identified. Once both the mission and the system architecture have been preliminary defined, before proceeding any further with the system design synthesis, it is important to verify whether or not all system requirements have been satisfied (Viola *et al.*, 2012).

The product architecture developed by a design team will have a tremendous impact upon customer satisfaction and market acceptance of the set of products offered by the firm (Yu *et al.*, 1999). Yet most work in architecture centres around cost savings, manufacturability, and other production-driven concerns. Yu et al., (1999) proposes a customer need basis for defining the architecture of products.

2.10Test design

Before testing or operating any hardware or system, a proper design must first be decided on. Engineering design creates the solution to a problem by producing hardware specifications. The design is functional and reliable when translated to hardware. The reliability of the design is determined by the functionality over a set period of time and the specified range of environments. The system is mostly designed to be reliable, maintainable and most of all, available (Misra, 2008). When a new system is deployed or when maintenance is completed, the system must be tested to ensure reliability. The success of the design is determined by different factors and may include time, cost, resources, scope, etc. To ensure the realisation of benefits for any given project, a test is performed. This test may be a prototype or full operations for a test period of time before permanent operations commence. It is therefore important for design requirements to be unambiguous, measurable, traceable, consistent and acceptable to key stakeholders (PMBOK, 2013). By specifying unusually tight tolerances or use of exotic materials, the reliability of the system may be increased by design, but generally at the expense of producability (Misra, 2008). Trade-off situations are unavoidable, often a designer may lower the reliability to save on materials, and instead increase the maintainability. Mirsa (2008) states that designers should disclose the fact that trade-offs have been made and management should have the necessary information to make a deciding decision.

The department of defence of the United States of America explain in their 2008 systems engineering guide for systems-of-systems that when evaluating the success (design, operation etc.) of a system, there are certain best practices that are vital:

- Testing and evaluation should proceed as an evidence-based approach. This is due to systems having asynchronous developmental paths;
- Develop analytical methods to support planning and assessment. Analytical methods may be used to to validate the requirements allocations to systems, and provide an analytical framework for systems-of-systems level capability verification;
- Independent evaluation. Compare and evaluate the system to other networks for optimisation;
- Diverse assessment. The system should be assessed over time in different environments to get and accurate result;
- Clear communication. A robust feedback process allows for continual evaluation of the system and creates opportunities to identify operational problems and make improvements.

2.11 Reliability engineering

Consider the definition proposed by the Advisory Group on Reliability of Electronic Equipment (AGREE) in 1952 and reported in AGREE (1957): Reliability is the probability of performing without failure, a specific function under given conditions for a specified period of time. The definition constitutes five basic terms:

1. Probability: The likelihood of failures to occur and is indicative of the reliability;

2. Failure: A clear understanding of failure is important as any part / instrument not performing to design specifications have failed the system;

3. Function: Instruments should only be used for their intended function, if not and breakage occurs, this may not be considered a failure;

4. Conditions: The design limitations of instruments should not be exceeded for operating conditions. If not and breakage occurs, this may not be considered a failure;

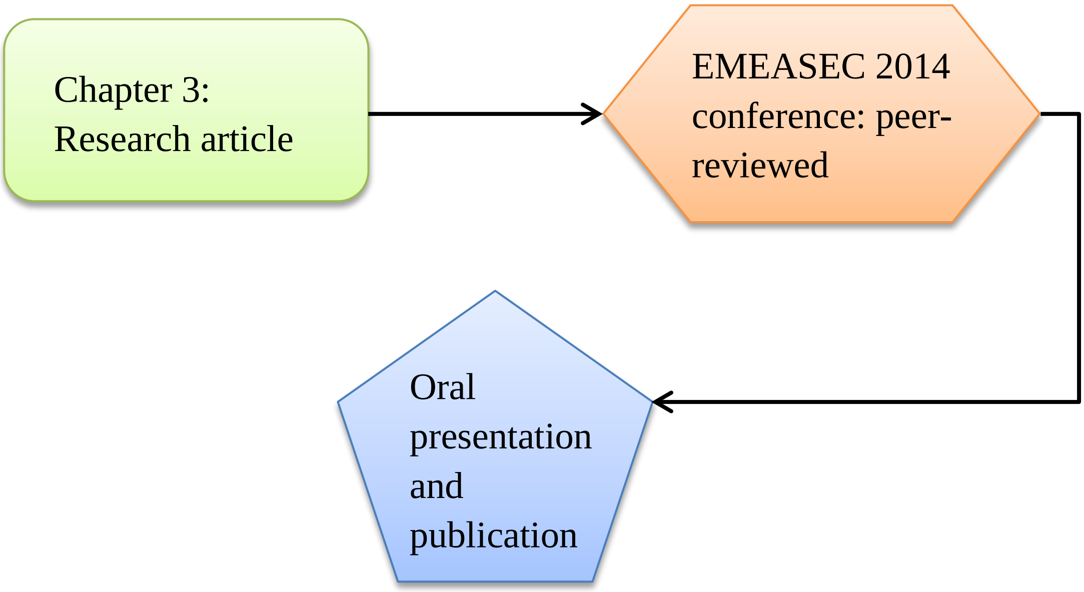
5. Time: The system must operate for a period of time, reliability may not be calculated without relating to the operational time.

However, the reliability of the system cannot simply be given without considering the reliability of the sub-systems. Once the probability of failures for each part has been determined, e.g. compliance test, the accumulative effect (reliability) of the system may be determined. The calculation of the reliability of these systems and sub-systems are often presented in the form of a reliability block diagram (RBD). The RBD shows network relations by performing system reliability and availability analysis. The structure of the RBD correlates with the physical arrangement and logical interaction of failures within the system. The system of the RBD contains direct and parallel lines. All of the parallel lines must fail for the system to fail (Yoshikawa & Zhang, 2014).

2.12 Conclusions

From the above chapter it is clear that Systems Engineering and associated Systems Management techniques possess highly valuable tools. In Chapter three these tools will be applied to the newly established atmospheric monitoring station at Welgegund. Although there are many tools and methods in Systems Engineering, the aim of this dissertation is the application of Systems Engineering and Management processes to the deployment of the SOI. The focus is to fulfil the need of the sponsors, stakeholders and clients. It has been said that a need exists to develop more advanced tools for Systems Engineering (Sage & Rouse, 2009). The author believes the model presented in Chapter three addresses the knowledge gap of trans-disciplinary awareness for continuous improvement by using the Systems Engineering approach.

Chapter 3



3 Introduction

Chapter 3 contains the manuscript in the equivalent format in which it was intend for EMEASEC 2014.

3.1 EMEASEC 2014 conference

The official website of the conference gives the following information: “The EMEASEC is the continuation of the biennial European Systems Engineering conferences (EuSEC). EMEASEC 2014 is the first Sector conference (of the International Council on Systems Engineering (INCOSE)) outside Europe and the premier conference of systems engineering and related disciplines in the Europe, Middle-East and Africa (EMEA) Sector. The conference gives industry, organizations, educators, researchers, and government the opportunity to showcase cutting edge practice and research. EMEASEC takes place 27 – 30 October 2014 at the Lord Charles Hotel and Conference Centre, Somerset-West just outside of Cape Town, South Africa. Papers submitted to EMEASEC 2014 were peer-reviewed and officially recognised as such and earned publication credits. The following ISBN has been allocated to EMEASEC 2014. ISBN: 978-0-620-58907-9.” Comments from the reviewer were positive:

3.2 Reviewer comments

PAPER: 39

TITLE: A Systems Engineering approach for the deployment of an atmospheric monitoring station

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--------------------------------------- Anonymous Reviewer ---

A thorough and detailed paper that applies a systems approach through the lifecycle. I particularly appreciated the detailed treatment of the context and stakeholders.

A Systems Engineering approach for the deployment of an atmospheric monitoring station

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Abstract. In this paper the importance of a Systems Engineering (SE) approach is reiterated for developing and managing an atmospheric monitoring station. A newly established comprehensive atmospheric monitoring station, the Welgegund Atmospheric Monitoring Station (WAMS), was used as a case study - system of interest (SOI). In agreement with commercial projects, the Customer Need has shown that the SOI life-cycle may be time intensive with significant financial impacts. The Operational Concept was visualised in terms of physical requirements, operational methodology and final deliverables. Functional Analysis emphasised the design importance of the measurement station for continuous operation and to remain relevant throughout the system life-cycle. Physical architectures and interfaces were scrutinised to maximise the efficiency of the SOI. Testing was vital and remains a continuous process. By continuing to implement the SE approach, the WAMS will satisfy the changing and unique stakeholder requirements throughout the system life-cycle.

The paper concludes that the SE framework provided made a positive contribution since the initial design and has adequately identified all the requirements in order for WAMS to be implemented on time, within budget and to the level of performance required.

Introduction

Monitoring temporal changes in atmospheric pollution on local, regional and global scales are of extreme importance in order to mitigate adverse effects on human health and the environment, especially relating to long-term effects such as climate change (Venter *et al.*, 2012). While there is a general agreement that atmospheric pollution must be monitored, less emphasis is often placed on the goals that must be achieved and the specific measurements that should be conducted during atmospheric monitoring. Monitoring atmospheric pollution should at least be aimed at early detection with optional long-term sustainability. Due to the unstable nature of ownership, available funding and the retention of expertise, successful succession may become an obstacle. Atmospheric pollution monitoring is also often hindered by geographically restricted and site-specific effects (Usero *et al.*, 2010), which may lead to regional and local data being inefficient in providing information to the local air quality manager. Scholes et al. (2009) pointed out that problems associated with the maintenance of comprehensive atmospheric measurement stations in specifically Africa are underestimated by the scientific community in the developed world. In order to minimise complications, lower learning curves and promote ease of access to quality data, proper initial development and automation of atmospheric monitoring stations are vital.

Atmospheric monitoring forms an integral part of environmental management and must include three basic tasks: data capture, data analysis and decision making (Petäjä *et al.*, 2013). All environmental problems are dynamic, which exhibit spatial and temporal dimensions. Ideally environmental monitoring should be conducted within a continuous space and -time frame (Ferreira *et al.*, 2000). Atmospheric monitoring site design and spatial deployment have in the past relied on experience, intuition and subjective judgement (Illston *et al.*, 2008). A holistic approach is needed to optimise system design according to specifications with regard to site selection, site design, maintenance and quality control. The approach should be cost-effective and deliver quality data, while adhering to social, economic and environmental constraints (Usero *et al.*, 2010).

Holistic views of the interaction between different monitoring systems and the complexity behind their management are seldom understood by disciplines without an engineering background (Islam & Islam, 2012). As a result, it may be challenging for professionals to interact and coordinate between different disciplines, branches or sectors outside their own specialities. Therefore, a knowledge gap exists that links practical industry related science, such as engineering, to more fundamental and theoretical sciences.

The Welgegund Atmospheric Monitoring Station (WAMS) is a newly established comprehensive atmospheric monitoring project in South Africa (Beukes *et al.*, 2014) that was used as a case study in this investigation. In an effort to stimulate informed decision making when establishing similar future projects, the well-known Systems Engineering (SE) methodology viz. Customer Need, Operational Concept, Operational Constraints, Organisational System Boundaries, Functional Analysis, Implementation Architecture and Design Testing, is applied to the WAMS system and the preceding measurement campaign studies in this paper. From the applied SE concepts the design and functioning of WAMS is revealed. Validation of the successful establishment of WAMS is supported by an example of calculating the measurement station (system-of-systems) efficiency. The SE approach is used to systematically describe the processes involved in moving from concept to design, and finally testing the system of interest (SOI). The research method was used to illustrate how SE thinking could be applied to improve the decision making process in the establishment of a comprehensive atmospheric monitoring station and ensure data quality that would contribute to the knowledge of atmospheric sciences on a local, regional and global scale.

Customer Need

At the Unit for Environmental Sciences and Management of the NWU, one of the aims is to preserve and improve the air quality for the citizens of South Africa (SA). The need exists for long-term observations that would improve future climatic scenarios in continental Africa and thus facilitate better mitigation procedures. In order to accomplish this, statutory agencies must be able to evaluate the status of the atmosphere by comparison to clean air standards and historical information. This is achieved by data acquisition from private, commercial and academic sectors. Goodpaster (1991) explains the term “stakeholder” to have been invented in the late 1960s as a deliberate play on the word “stockholder” indicating that other parties than those holding equity positions have a “stake” in the decision-making process. The stakeholder requirements for the WAMS were gathered and these comprised mainly of strategic requirements of a business nature. Since 2004 South Africa has implemented new air quality standards and established the South African Air Quality Information System (SAAQIS).

SAAQIS “makes data available to stakeholders including the public and provides a mechanism to ensure uniformity in the way air quality data is managed i.e. captured, stored, validated, analysed and reported on in South Africa” (DEA, 2012). Since the introduction of the National Environmental Management: Air Quality Act 39 of 2004 the need for atmospheric monitoring and acquisition of high quality atmospheric data to mitigate possible adverse health effects has drastically increased.

In order to improve the knowledgebase, governments and academia of SA and Finland decided to join forces, forming the project sponsors. It was decided that criteria pollutants, as stipulated by SA government, should be measured. An Operational Concept was envisioned that would satisfy various stakeholders such as the scientific community, industry and academia, in addition political ties between SA and Finland would be strengthened.

The WAMS is co-owned and sponsored by three entities viz. North-West University (NWU), University of Helsinki (UH) and the Finnish Meteorological Institute (FMI) as indicated in Figure 1. The sponsors (also stakeholders) envisioned the public and environment to be the final beneficiaries in terms of health; however immediate beneficiaries included academia, policy makers and industry. Various other agencies, companies, institutions and universities formed part of the clients as shown in Figure 1. These clients (often stakeholders) had diverse interests and service delivery requests such as data quality, specific measurements, research, training and field testing. Each client’s time frame varied as some were specific to a single objective while others span the duration of the project.

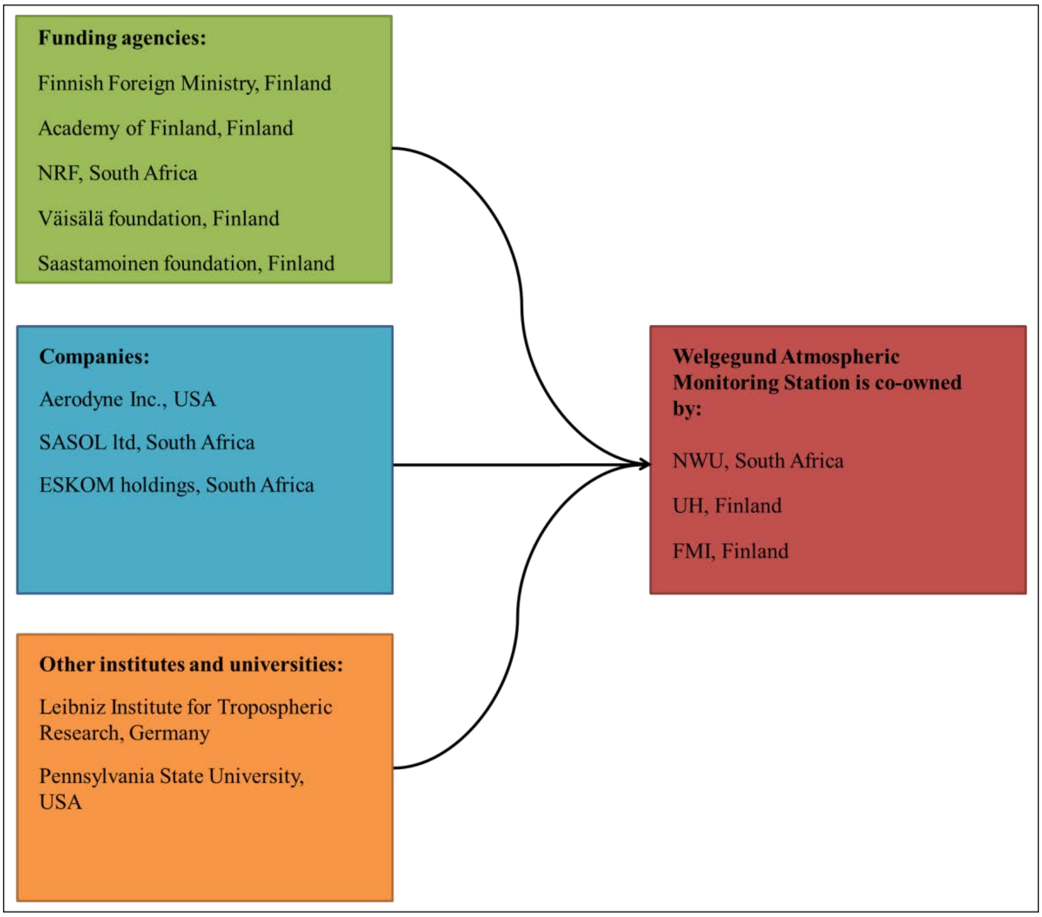

Figure 1: The major current and past stakeholders associated with the WAMS project.

Each stakeholder required clarity on funding and the work allocation within the specific timeframe. This was discussed in open communications with clear set objectives that could be validated and the net product, in this case data, verified. Seamless integration of individual measurement campaign studies with each other and the SOI (WAMS) remains of great importance, since interruptions and hardware conflicts affect several stakeholders and their objectives. The stakeholder requirements captured and prioritised the activities needed (such as quality control and quality assurance) to satisfy the outputs by means of clear traceability i.e., a daily electronic diary containing all activities on site available for stakeholder access. Further traceability transpired by means of additional data from other measurement campaigns, previous studies or permanent measurements at WAMS being made available to stakeholders for comparison and verification.

Clients and stakeholders listed in Figure 1 had certain functional, operational, technical and transitional requirements that defined the manner in which measurements were carried out as well as the specific timeframe to achieve the goals. For any given project the stakeholders called for:

- Functional requirements that included on-site visits, local support, security, site scientist, online access and calibration accuracy
- Operational requirements, that include high-level functional requirements, were met by trained staff aimed at inspection and maintenance, a reliable power supply, internet access and calibration supplies;
- Technical requirements that included logistics and ease of access, standard operating procedures, timers for automatic start and stop procedures, uninterrupted power supplies and time delays for protection against power surges, increased vacuum or compressed air supply;
- Transitional requirements that required skilled manpower. Personnel or training provided by the stakeholder as well as flexibility and spacious design at WAMS in order to ensure smooth integration.

At the end of the measurement period, instruments were decommissioned and repossessed by their owners unless otherwise stated in the stakeholder requirements. Data was in most instances the mutual property of the clients, stakeholders, owners and sponsors, therefore it was typically agreed to produce a research paper, conference proceeding or technical note with contributing authors from both the technical and academic disciplines. However, the raw instrument data was seldom immediately ready for publication but instead required rigorous processing before valuable information could be obtained. The processing period and actual scientific writing was often time intensive due to post graduate students requiring training and being involved in several projects in parallel. The due dates for final deliverables and project sign-offs have in some instances been prolonged for years after the instrument measurements were discontinued. Keeping the extended processing period in mind is vital when funding and project timeframes are discussed during the initial requirements of a project.

Once the Customer Need and Stakeholder Requirements have been captured, a detailed Operational Concept was compiled. In this paper the Operational Concept discusses the objectives and the rationale of establishing WAMS.

Operational Concept

As defined by the operational concept, the main objective of this project was to establish a permanent long-term continuous atmospheric monitoring station that would produce high resolution data with high quality. The principal aim was the collection of regionally representative atmospheric data in the interior of southern Africa and thereby addressing a knowledge gap existing in the local and global community. The SOI constituted three phases, namely two extensive measurement campaign studies (Botsalano and Marikana) and fixed long-term measurements (Welgegund). The two measurement campaign studies were conducted in order to obtain an improved spatial quantification of atmospheric species at a background region and an industrially impacted area, respectively and the third phase entailed the establishment of a comprehensive long-term atmospheric monitoring station (WAMS). The aims of the operational concept were to:

- Provide broad spatial coverage in the interior of SA through two measurement campaign studies and long-term monitoring (WAMS);
- Investigate influences of air quality priority areas declared by the SA government and other source regions;
- Facilitate capacity building and knowledge transfer.

WAMS is a research station and training platform for students with very few permanent staff members. Measurements, individual measurement campaigns, field checks and calibrations are preformed mainly by students. Two main phases were identified in managing the project, an input phase and an intermittent phase. Welgegund is mostly operated in an intermittent phase, i.e. autonomously and staff self-reliantly according to custom standard operating procedures (SOPs). Input phases are initiated when major system improvements are undertaken; this is done when required or when opportunities arise. These input phases include site expansion, instrument addition, general maintenance and instrument service.

The establishment of WAMS and the preceding measurement campaigns were conducted by performing detailed requirement analysis of the afore-mentioned aims. Further operational strategies such as risk analysis, risk management, configuration management and information management were considered for the infrastructure and operating personnel at WAMS to maximise quality assurance and safety. The principal functional requirements at WAMS were to:

- Enhance the capturing of local anthropogenic and natural events;
- Investigate local and regional transport of atmospheric species;
- Explore the interaction of atmospheric species originating from fresh and aged air masses;
- Obtain background measurements (no large point or regional pollutant sources);

- Facilitate environmental and health impact studies;
- Provide quality data contributing to national and international legislative procedures;
- Address the knowledge gap for the under-sampled southern hemisphere.

Management is an important element of any successful operation. Management makes out the core function of an organisation and is integral to profit and non-profit organisations. During operations at the SOI, management was responsible for the planning, coordinating and controlling of resources and services of the business function. In Figure 2 the management structure transforms inputs from the project sponsors and owners in the form of concepts, knowledge and assets into outputs desired by the clients, affecting stakeholders and satisfying beneficiaries. As mentioned previously, the SOI is co-owned by the NWU, UH and FMI, and managed by the Atmospheric Chemistry Research Group (ACRG) at the Potchefstroom campus of the NWU, together with intermediate support from UH and FMI. The ACRG is managed by lecturers and researchers, while the UH and FMI each has their own management structures. The lecturers and researchers from the ACRG relied on senior personnel in the academic environment such, as post-doctoral candidates, to administrate and coordinate operations at WAMS where senior students then provided operational support and ensured data quality. Depending on the need of the clients and stakeholders, the lecturers and researchers would discuss the status quo with the heads of departments from the affected industries. Specialists and advisors would then be consulted before changes in the operational procedures of the SOI would take place. Any changes or upgrades would then be administered by the appointed contractors and/or technicians with subsequent knowledge transfer by means of training and workshops to secure sustainability. In the management structure of WAMS:

- The group leaders of the ACRG replaced as much as possible hierarchic structures by roving responsibilities and allocated task or campaign orientated formation of small teams with their own responsibilities;
- Field staff (laboratory technicians and students) had been trained to perform primary measurements and checks;
- Senior post-graduate students, laboratory managers and group leaders were responsible for plausibility analysis, data cross-checking and reliability analysis;

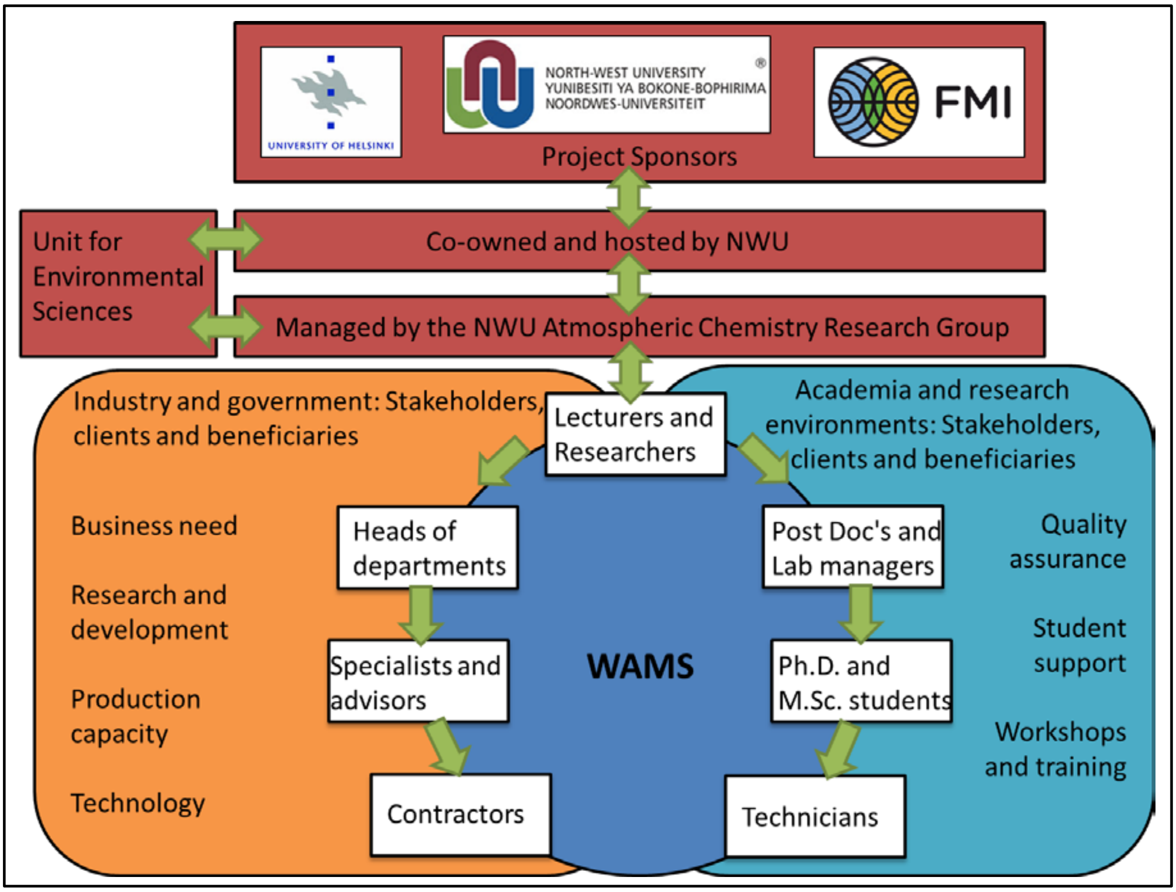

Figure 2: Management structure of WAMS SOI under the NWU umbrella with inputs from collaborations such as UH, FMI, industry and academia

In order to further unify the management function of our SOI in the Operational Concept, the operational flow and management at WAMS is depicted in Figure 3. The project sponsors always headed operations and were informed weekly on all activities. This enabled the sponsors to remain involved and provide informed decision making. Major expansions and upkeep (such as calibrations) were conducted by a station manager and senior students. This was brought on by a necessity from within (e.g. out-dated instrumentation), or initiated by an external input such as a new field of study specified by collaboration partners. Maintenance and upkeep was generally performed by junior students in training and temporary employees – all which were supervised by senior staff. Periodic data processing and quality control was performed by all staff in order to maximise efficiency and knowledge transfer.

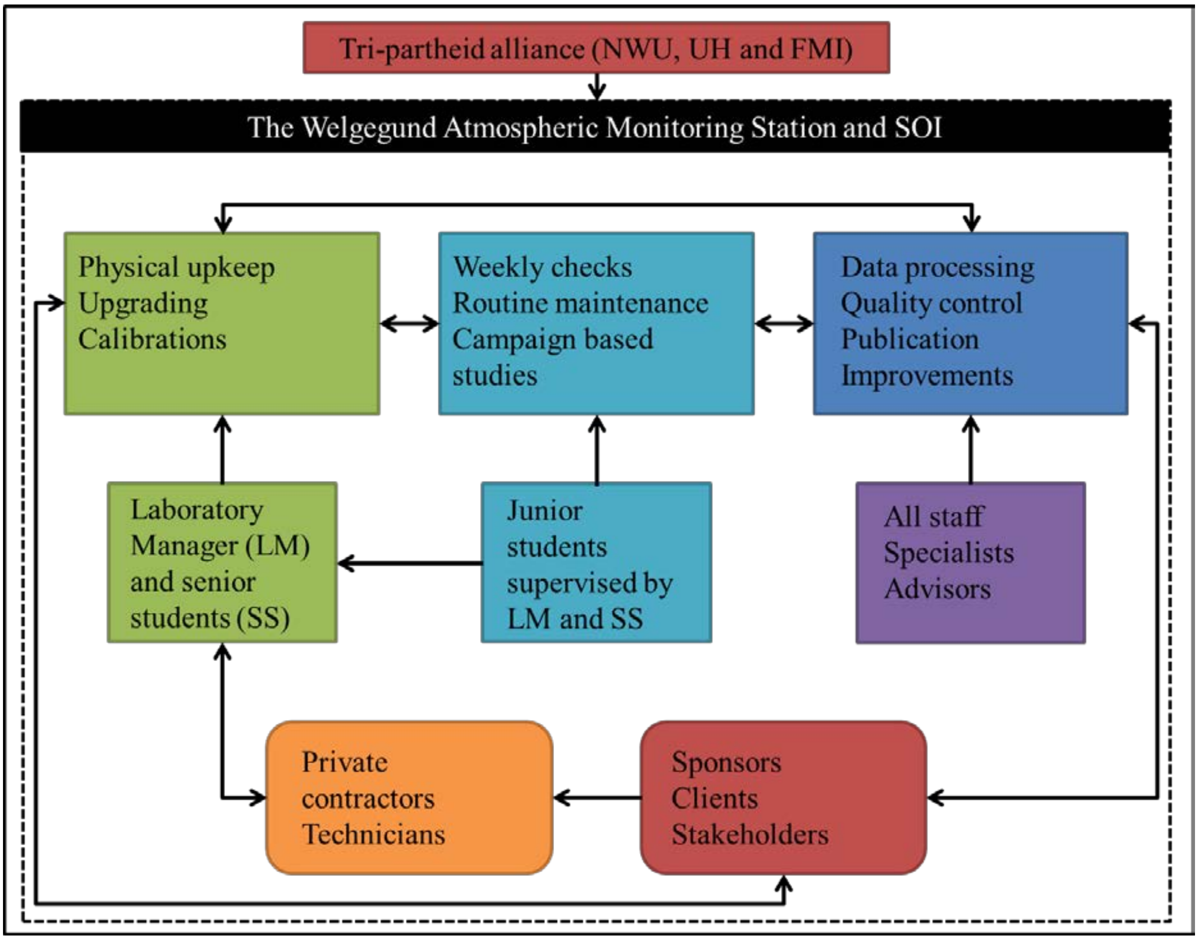

Figure 3: Operational flow diagram of the WAMS SOI depicting the physical upkeep, weekly checks and data processing as well as the responsible staff and their hierarchy

The Operational Concept was frequently met with many limitations and managerial challenges which especially occurred during the establishing phase of the SOI. However, these constraints needed to be explored and understood in order to minimise the threat and to secure the future of WAMS. The constraints are discussed in Operational Constraints and Organisational System Boundaries.

Operational Constraints

In any project certain aspects will cause a bottleneck. When deploying the SOI, challenges arose that hindered the scientific productivity. The NWU ACRG is an academic institution that prioritises education and training. This limits the student number and retention of students after their Ph.D. studies since industry competitive salaries are not feasible. A challenge therefore exists in maintaining the WAMS since a limited number of staff positions exist and pressure to continuously increase the number and complexity of instrumentation remains.

Management identified the following top Operational Constraints considered to hinder the SOI:

- Persistent irregular funding periods as a majority of financial sources were project specific;
- Continuing uncertainty in collaboration time extent;
- Persistent loss of expertise since most employees was students being trained for the private sector;
- Remaining uncertainty in WAMS location as the SOI is not situated on property of the NWU, but on a commercially owned farm.

Scientific productivity remains vital for continuation of the WAMS especially in securing funding since it is the final deliverable and a quantitative measurement of importance to the local and international community. It was decided that by increasing and maintaining the scientific productivity of WAMS Operational Constraints could be mitigated to a large extent. The continual progress in publication outputs underlines the importance of WAMS to the local and international community, thereby generating new and prolonged collaborations, student exchange programs and funding opportunities. However, the constraints above posed certain managerial and administrative boundaries.

Organisational System Boundaries

In this paper, the Organisational System Boundaries are defined as the administrative boundaries that need to be surpassed in order to secure a future for the WAMS. The initial System Boundaries were crossed when high resolution, high quality data was available for publication. With the crossing of each set of boundaries, new opportunities arise and the next tier develops, in this section the most recent boundaries of the SOI, in order to secure long term sustainability, are presented. The constraints as mentioned above were written in the form of achievable goals, each goal being a boundary. It must be noted that with the concluding of individual projects and close of each financial year, certain aspects of the SOI may once again fall below the Organisational System Boundaries and may need to be revised. The Organisational System Boundaries at publication date included:

- Securing governmental funding and input;
- Increasing collaboration;

- Expanding research opportunities to students, overlapping individual research campaigns and employment timeframes;
- Establishing contractual agreements between partners, clients, stakeholder and service delivery entities;
- Underlining the scientific importance in the local and international community;
- Integration and collaboration in a variety of scientific domains;
- Receiving formal global accreditation by joining global networks e.g. Global Atmospheric Watch (GAW).

Considering the complex nature of activities undertaken at WAMS, collaboration remains vital for the implementation of new technologies and maximising scientific value from collected data. In this way the NWU, UH and FMI have collaborated extensively. The NWU managed the intermittent phase, while the UH and FMI largely contributed during the input phase. Collaboration opportunities allowed for exchange in expertise and an increase in staff which has lessened the financial burden either directly or indirectly. Furthermore, collaboration has created opportunities and exposure to diverse scientific domains - the importance of collaboration must therefore not be understated.

The Operational Concept, Operational Constraints and Organisational System Boundaries of WAMS and the preceding campaign studies needed to be designed and implemented keeping the total life cycle in mind. The concept needed to be visualised in terms of physical requirements, operational methodology and final deliverables. This can be seen in the high-level Functional Analysis.

Functional Analysis

In Figure 4 a functional analysis presents the life cycle approach for establishing WAMS and the preceding two measurement campaign studies – the total SOI. It is important to visualise the life cycle and processes of the SOI as this sheds more light on the managerial constraints and boundaries as discussed previously and allows for future deliberation. Five functional blocks (FB) were identified that range from conceptual design to the desired outputs of the system. In FB 1 the need for the project was discovered and consequently station design was initiated. The design strategy was reliant on good communication between the respective sponsors, each with their specific needs. FB 2 contains the two initial measurement campaign studies and the final founding as a permanent station. This was based upon a balance between the sponsors' needs and scientific constraints. The fundamental processes investigated at the station are shown in FB 3. FB 4 represents the actual operation and measurements at site. The setup and operation, especially during the establishment, was heavily dependent on experienced personnel such as scientists and technical staff. The final outputs were in the form of scientific research papers, conference contributions and technical reports, indicated in FB 5. The location of decision making and the rationale of each FB are presented in Table 1. From Table 1 the progression and knowledge transfer between Finland and South Africa is evident.

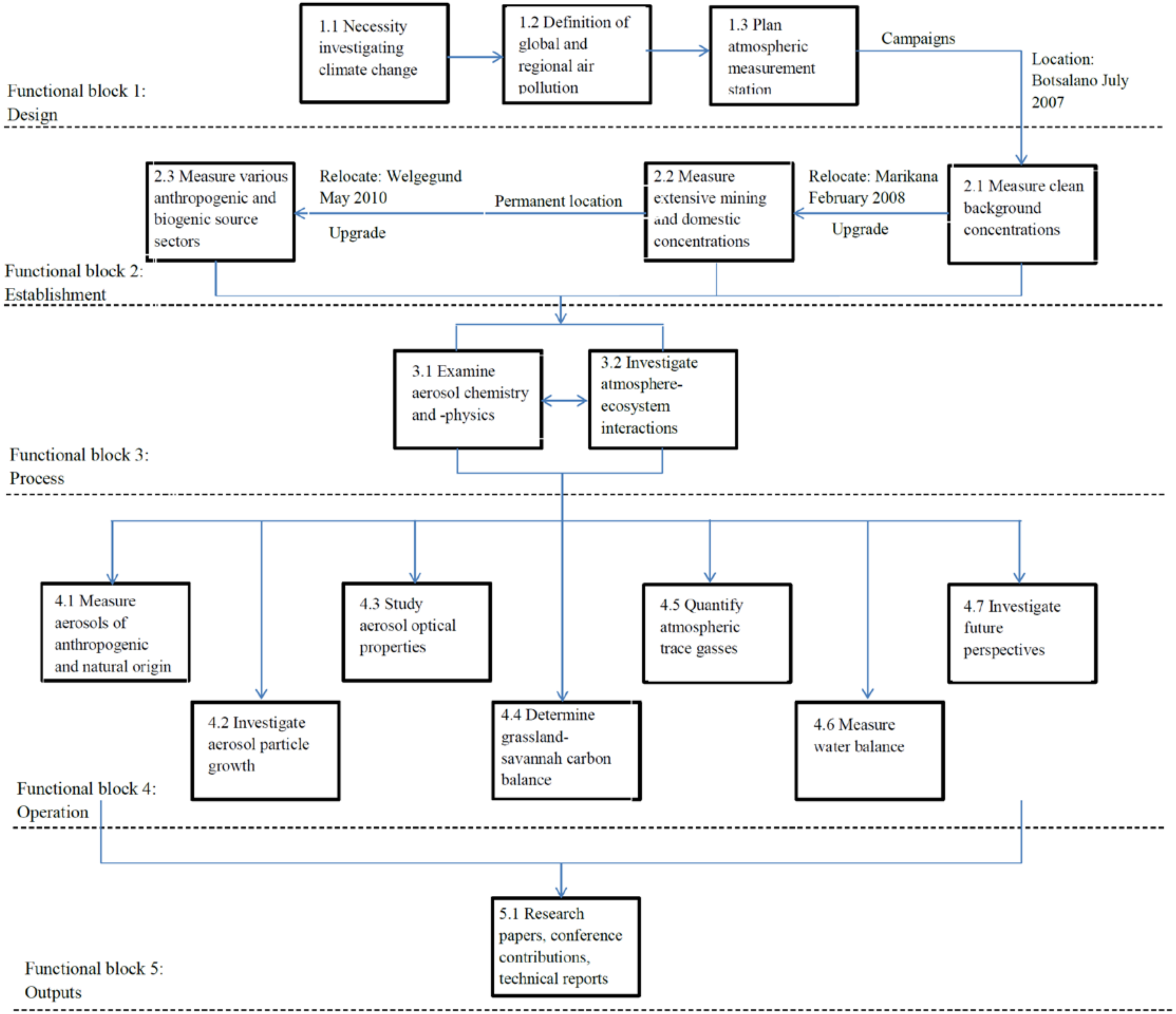

Figure 4: Functional analysis for the design and establishment of the Welgegund Atmospheric Monitoring Station

Table 1: Rationale of the WAMS evolution as related to the various functional blocks

Functional block	Location	Rationale
1.1	Helsinki - Finland	Under sampled southern hemisphere Permanent monitoring station addresses knowledge gap
1.2	Finland and South Africa	Southern Africa has well defined pollution source sectors Long range transport of atmospheric species needs further investigation Priority areas are declared by government
1.3	Helsinki - Finland	Increase scientific knowledge in atmospheric physics and chemistry in southern Africa Train NWU students in atmospheric sciences Funding from Finnish foreign ministry Long-term measurements
2.1	Botsalano - South Africa	Co-owned by NWU and UH, managed by UH and NWU
2.2	Marikana - South Africa	Co-owned by NWU and UH, managed by UH and support by Rustenburg local municipality (AQ)
2.3	Welgegund - South Africa	Co-owned and managed by NWU, UH and FMI Funding from various stakeholders Various institutes, universities, agencies and companies collaborate
3.1	Welgegund - South Africa	Measurements are conducted by physical and chemical analysis Results give feedback and allow for improvement of measurement processes
3.2	Welgegund - South Africa	Short - and long-term impacts of pollutant species need to be investigated
4.1 - 4.7	Welgegund - South Africa	Regional transport of atmospheric species is investigated Quantify species of natural and anthropogenic origin
5.1	Finland and South Africa	Research papers, conference contributions and technical notes are the final deliverables

Functional Analysis emphasised the importance of the physical and managerial design of the measurement station for continuous operation throughout the project life. Physical architectures and interfaces needed to be scrutinised to maximise the project efficiency.

Physical - implementation architectures and interfaces

The SOI is a system of systems (Operational Concept, management, physical structure, operations and science) therefore the design began with examining the centre architecture (physical structure of the monitoring station) and data flow between the various sub-systems. In Figure 5 the nested SOI systems are presented. The Operational Concept and various sub-systems were conceived when management ensured the successful integration of concepts to the physical structure, i.e. monitoring station. The operations team continually operate and maintain the monitoring station providing feedback to management and sponsors. Periodically generated scientific outputs further credit or discredit operations leading management to update and complement the Operational Concept as well as associated constraints and boundaries. For the discussion in this section, the monitoring station system will be discussed.

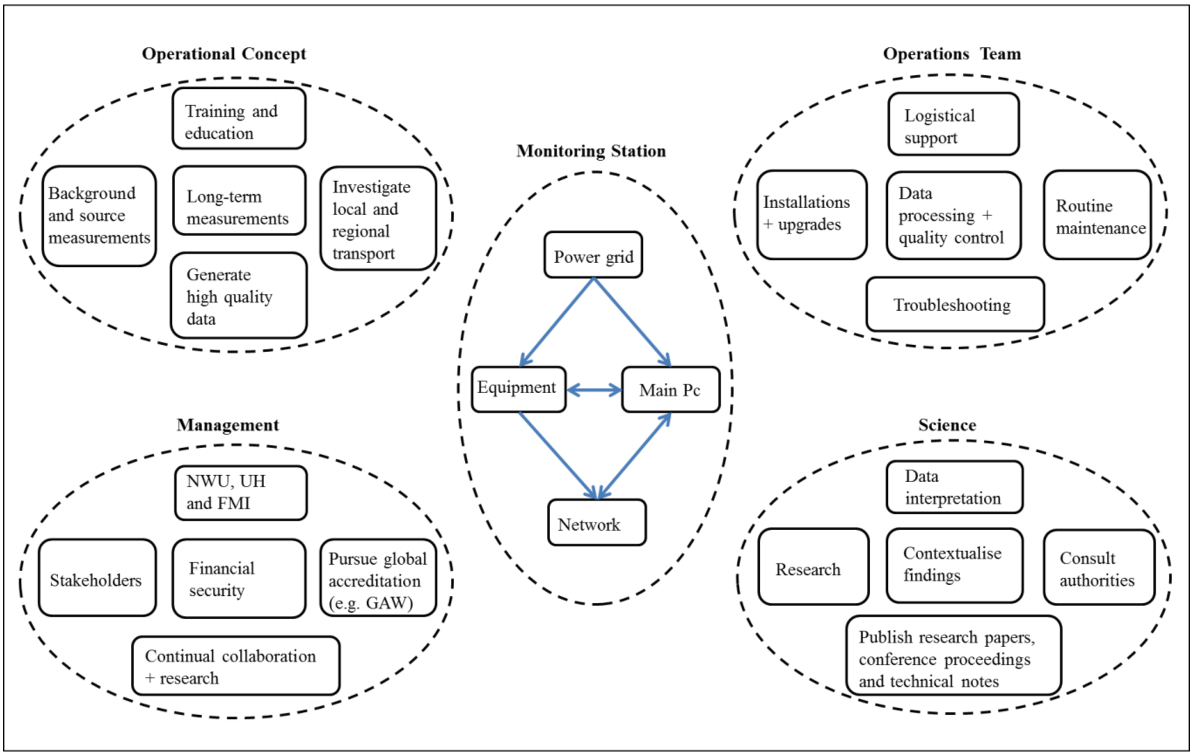

Figure 5: WAMS and the preceding campaign studies are considered systems-of-systems

An important factor in establishing WAMS was the optimal physical positioning in order to maximise the number of atmospheric parameters that could be monitored, increasing the scientific output. However, the ease of logistical support in terms of maintenance and upkeep received priority since the measurement systems (gaseous, aerosol, meteorological) are interdependent and crisis management and support should be swift.

The measurement equipment (Figure 5) was accommodated in a mobile trailer (Eurowagon 2000) as the initial two measurement campaign studies (phase one and phase two of the SOI) needed relocation options (Petäjä *et al.*, 2013) before being moved to the permanent location at Welgegund (phase three). Although a sea container would prove more efficient in lightning protection at WAMS, it would have been less mobile during the two sampling campaigns at Botsalano and Marikana, and therefore compromise the aims of the project. The power input in Figure 5 specified that the trailer converted 3-phase electricity to supply instruments with 220 V AC power. The incoming power connects to surge protectors and a time delay switch that remains off for 4 minutes after a power break occurs in order to curb sudden spikes when power feed returns. From these power outlets, the power supply goes through an online UPS that further protects instruments against power surges. Extra care was taken in grounding the measurement systems. A 10 mm copper wire shields a 15 m diameter around WAMS with the wire running up a 10 m mast and a 5 m mast. All signals generated outside the trailer join at a circuit board equipped with transient suppressors before entering loggers and the master PC inside the station.

A design requirement was for the SOI to generate high resolution data, therefore the master PC gathers measurements and diagnostics from all instruments every minute. After midnight, all text files containing the previous day's data are compressed and sent via a cellular modem to an online server for backup and allowing stakeholders access from a central location. During office hours, the complete set of data from the previous day is downloaded for inspection and interpretation. Preventative and also emergency maintenance can be done accordingly.

Testing forms an integral part in the project life cycle and is a continuous process. Testing is a form of validation and may first be done internally by the NWU, UH and FMI before being scrutinised by external evaluators.

Test Design

Physical and measurement systems were tested in isolation before being combined in the Eurowagon and shipped to SA. Testing included functional, overload and failure mode testing. Although every precaution was taken when assembling and integrating the measurement instrumentation, only field testing could accurately portray the total reliability and availability of the system. The fault tree analysis (FTA) in Figure 6 performs the top down deductive failure analysis in which block diagrams show network relationships, reliability and therefore availability of the WAMS system. The structure of the FTA defines the logical interaction of failures within a system that are required to sustain system operation. Successful operational systems require at least one maintained path between the system input and the system output. Equations 1 – 3 below, were used to describe the minimum combination of failures required to cause a total system failure.

Assuming a homogeneous failure rate per unit of time, where MTBM is mean time between corrective and preventive maintenance actions, the operational availability (Ao), as seen by the user, is defined as:

$$A_o = \frac{MTBM}{(MTBM+MDT)} \qquad [1]$$

Where MDT is the mean down time. MTBM and MDT may be calculated for each individual process or system.

For example, if a component has a failure rate of 10 failures per 1000 hours and a 5 hour MDT, MTBM would be every 100 h and then its operational availability is approximately 95%. Calculated from Equation 1 we see the percentage yearly operational availability per component of the WAMS as depicted in Table 2:

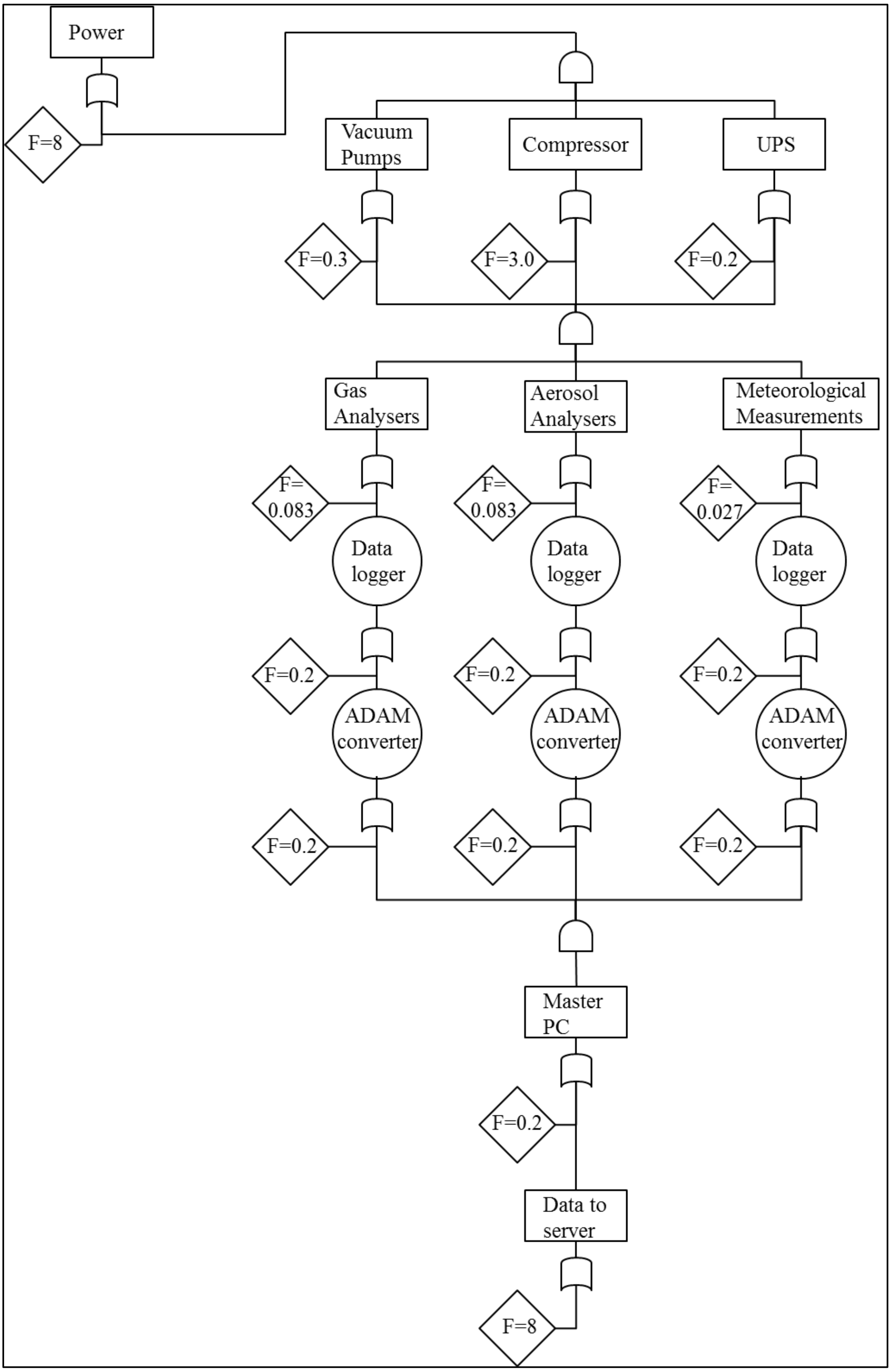

Figure 6: A failure tree presents the process of data acquisition. The amount of failures (F) is given per 744 hours (31 days). Although some systems are extremely erratic and unpredictable, an average experienced throughout the SOI lifecycle is provided

Table 2: The amount of failure events, mean time to maintenance, mean down time and percentage availability of various critical components at WAMS

Input	Failures (events per 744h)	Time (h)	Mean time between maintenance (h)	Mean down time (h)	Availability per year (%)
Power	8.000	744	93	3.0	96.9
Vacuum pumps	0.333	744	2234	2.6	99.9
Compressor	3.000	744	248	12	95.4
UPS	0.200	744	3720	1	99.9
Gas analysers and Aerosol analysers	0.083	744	8964	168	98.2
Meteorological instrumentation	0.027	744	27556	168	99.4
Data loggers and Adam converters	0.200	744	3720	12	99.7
Master PC	0.200	744	3720	24	99.4
Router	8.000	744	93	1	98.9

For components connected in series the availability (A) for component i to component *n* is given by Equation 2.

$$A = A_i A_{i+1} \dots A_n \qquad [2]$$

Considering parallel components Equation 3 is used:

$$A = 1 - (1 - A_i)^2 \qquad [3]$$

The operational availability of the WAMS is calculated by combination of Equations 1, 2 and 3 for systems in series and parallel. The equations are applied to the FTA diagram logic. Although WAMS is a system-of-systems, only Equation 2 (for components in series) will be used, since each individual system (gas, aerosol and meteorology) may function separately and provide essential data. The operational availability of each system is presented in Equations 4 and 5 below:

$$A_{gas+aerosol} = 0.969 * 0.999 * 0.954 * 0.999 * 0.982 * 0.997^2 * 0.994 * 0.989 \quad [4]$$

$$A_{gas+aerosol} = 88.5\ \%$$

$$A_{meteorology} = 0.969 * 0.999 * 0.954 * 0.999 * 0.994 * 0.997^2 * 0.994 * 0.989 \quad [5]$$

$$A_{meteorology} = 89.6\ \%$$

Therefore the overall availability of WAMS for the gas and aerosol systems are 88.5% each and 89.6% for the meteorological system. This agrees well with the percentage data coverage calculated for the gaseous (95.9 %), aerosol (93.4 %) and meteorological (94.6 %) systems (15 min averages) over two years. The main problematic components are the power supply, compressor and router, which are further discussed:

The main source of power is the South African national grid. Power supply in SA is erratic and in certain instances unpredictable because it depends on environmental conditions e.g. interruptions by electrical thunder storms and flooding during the wet season, the increase in national consumption and political circumstances. Although the power source is not that stable, it is considered to be adequate. In the design, inline UPSs had been placed between the sensitive instrumentation and the main power source. Mechanical instrumentation is not connected to UPSs due to their heavy load. In the event of a power outage the analysers remain protected and on standby, while mechanical components like pumps are switched off. Although this precaution protects the instruments, data loss still occurs because sample flow is interrupted. It is planned in future to deploy a stand-alone diesel electricity generator ~ 300m downwind of the measurement station. Although a small lag exists when switching between the national grid and power generated with the stand-alone diesel electricity generator, extended power outages will still allow for normal operation.

Compressed air is used to dry incoming sample air in order to prevent condensation inside the instruments, as well as to pneumatically operate valves when switching between sampling and calibration modes. The total flow rate through the system amounts to 12 L/min. A dental compressor with a 65 L storage container is currently used. Failures of the compressor are due to erratic power supply and a heavy duty cycle in a dusty environment that shortens the lifespan of the compressor motor. In future the dental compressor will be replaced with a heavy duty scroll compressor with a 300 L storage tank. This compressor will provide enough compressed air during short power failures and will also be more suitable to handle the heavy duty cycle.

From the main computer data is transferred via a router and modem to a server with the internet. The router is designed to remain on and always be connected. However, in practice this has proven not to be the case. The non- transfer of data is mostly associated with power failures and the router has to be manually restarted. In future, a timer will be placed on the router to manually restart it at midnight. With the installation of a stand-alone power generator as mentioned above, this problem will further be solved. If the problem persists, a better quality router will replace the current one.

Conclusions

This project was undertaken in an environment in which failure would have had financial impacts on the research group and further capacity building of students. Failure would furthermore mean loss of quality data and science to the local and greater scientific community. Good application of Systems Engineering during initial design adequately identified all the requirements that allowed the WAMS to be implemented on time, within budget and to the level of performance required.

The Customer Need has shown that the final deliverable, that is the publishing of scientific papers in the public domain, may be time intensive, especially, due to the processing period of the raw data. Therefore the final deliverable and sign-off on the project may be years after instrumental installation and measurements. It is important to consider the extended data processing period when funding and the project timeframe are discussed during the initial requirements of the project. The Operational Concept and Organisational System Boundaries of WAMS, as well as the preceding campaign studies needed to be designed and implemented by considering the total life cycle. It was required that the concept be visualised in terms of physical requirements, operational methodology and final deliverables. Functional Analysis emphasised the importance of the design of the measurement station for continuous operation throughout the project life. Physical architectures and interfaces needed to be inspected to maximise the project efficiency. Testing forms an integral part in the project life cycle and is a continuous process. Testing is a form of validation, which is firstly performed internally (NWU, UH, FMI) before being scrutinised by external evaluators. In this project, measurement instruments were tested and calibrated in isolation before being assembled into the measurement station system. The system as a whole was then further evaluated to ensure successful sub-system integration.

In order for the project to remain relevant and continue building a critically important knowledgebase for the better understanding of atmospheric species, and their associated health and environmental impacts, various campaign and short-term studies are frequently undertaken at the WAMS. The sponsors and clients of the various projects are often international and from diverse speciality fields. It remains vital to understand the requirements of the various sponsors, owners, clients and stakeholders to maximise the final output (e.g. field testing instruments or data acquisition) and ensure possible future collaboration.

The WAMS project and preceding measurement campaign studies have benefitted by adhering to the SE approach. This has led to the project remaining relevant in a changing environment and allowing for changes on both managerial and structural level. By continuing to implement the SE approach, the WAMS will satisfy the changing unique stakeholder requirements throughout the project life-cycle.

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Biography

Mr A.D. Venter is a post-graduate scholar at the North-West University, Potchefstroom Campus South-Africa. He is a Ph.D. candidate in atmospheric chemistry and an M.Eng. candidate in development and management. While environmental sciences are his major concentration, he aims to address sustainable development and climate change practically.

Dr. J.P. Beukes is a lecturer and researcher at the North-West University, Potchefstroom Campus, with extensive research and operational experience in the pyrometallurgical and environmental fields.

Dr. V. Vakkari is a researcher at the Finnish Meteorological Institute, Helsinki, Finland, with research focus on atmospheric aerosols and boundary layer dynamics.

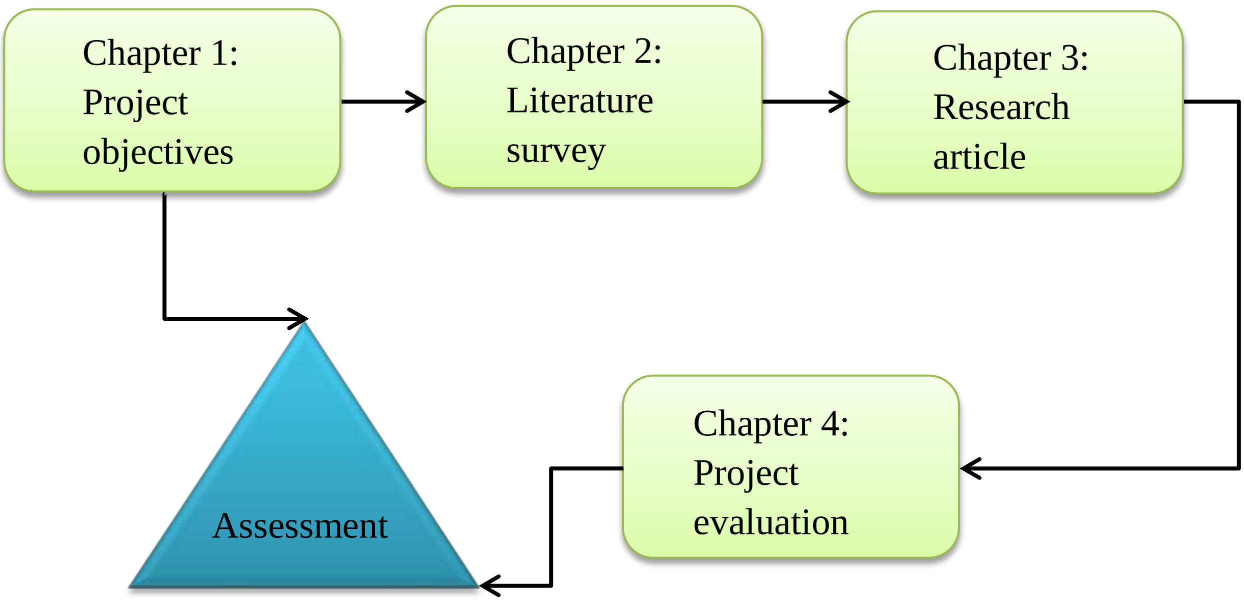
Dr. Johan Fick (PhD) A metallurgical and welding engineer by early training, turned small business entrepreneur in the early 80's where he gained a wide spectrum of technical and business management experience during a mid-career period, founding and running a number of technical services companies, and property development projects. He has had a parallel academic career, starting as part time lecturer at the then Potchefstroom University for Christian Higher Education in the mid 80's at the erstwhile fledgling faculty of Engineering, leading to the award of professorship in the department of Metallurgical Engineering in 1994. By 2003 he had divested himself of most of his business interests, when he was appointed as Dean of the Faculty of Engineering of North-West University, - the resultant Higher Education Institution which was formed by the merger of the PU for CHE and the previous University of Bophuthatswana. Having driven the concept of the founding of the Centre for Research and Continued Engineering Development (CRCED) he later joined the center as professor on completing an 8 year term as Dean. He now facilitates post-graduate courses in Entrepreneurship, Corporate Functioning and Project Quality Management, and has a research interest in Energy Policy.

Dr. Piet Stoker (PhD) is currently manager at the Centre for Research and Continued Engineering Development (CRCED) of the North-West University's Vaal campus. His career originated as an engineer at the Council for Scientific and Industrial Research (CSIR) where after he gained a wide spectrum of technical and business management experience in various companies, fulfilling the positions of CEO and Director.

Dr PG van Zyl is currently employed as a Senior Lecturer at the Potchefstroom Campus of the North-West University. His main research topics are in the fields of Atmospheric Sciences and Chromium *related research. He is currently author and co-author of 23 peer-reviewed research papers published in national and international accredited journals, and has several oral and poster conference contributions.*

Doc. Lauri Laakso is a head of a group at Finnish Meteorological Institute and extra-ordinary associate professor at the North-West University, Republic of South Africa. He has a long experience on environmental research and development of experimental facilities in challenging environments. Dr Laakso received his PhD in physics at the University of Helsinki, Finland in 2004 and was nominated as an adjunct professor in Aerosol Physics in 2007. In 2008-2010 he was working as a visiting professor at the North-West University, Republic of South Africa. Home-page: http://en.ilmatieteenlaitos.fi/cv-lauri-laakso

Chapter 4



4 Introduction

In this chapter, the project is evaluated by considering the success and shortcomings encountered for each objective of this investigation. Future recommendations are suggested.

4.1 Project evaluation

It may be a challenge interacting and coordinating projects with different disciplines, branches or sectors outside of a speciality project. This study has bridged the gap between industry related sciences such as engineering to more fundamental and theoretical sciences. A framework has been provided that highlights the techniques of Systems Engineering and provides an understanding for the need and process of atmospheric monitoring. The specific project objectives were:

Objective I: Develop an Operational Concept for the WAMS project indicating typical short, mid and long-term goals applicable to other new, as well as established measurement stations.

An operational concept was developed. Precise short, mid and long-term goals were not identified as such, since it was found that each system-of-interest would be met with unique opportunities and challenges. Instead, the overarching aims of the WAMS-system may be seen throughout the operational concept and system boundaries, leading the readers of new – and established atmospheric monitoring stations to identify and apply appropriate goals as required. The aims and functional requirements of the operational concept were investigated. The management structure and operational flow diagram were derived from the operational concept.

Objective II: Define the system boundary by investigating possible project weaknesses and proposing solutions.

The operational constraints indicated the boundaries and limitations faced when establishing a measurement station such as the WAMS. Solutions were proposed to minimise the risk of the system boundaries and ensure long-term sustainability. It was established that scientific productivity and inter-disciplinary collaboration remained vital for continuation of the WAMS. This may be achieved by constructing an integrated development program, for current and new atmospheric measurement stations, in order to ensure sustainable measurements resulting in quality data generation.

Objective III. Investigate the customer need and stakeholders relationships within WAMS

The customer need was investigated and documented together with the WAMS stakeholders and their typical requirements (functional, technical and transitional). Information was obtained through personal communications with the project sponsors from both Finland and South-Africa, management, the technical operational team and personal experience. In SA, government (municipalities) has increased its customer need since atmospheric monitoring became compulsory. Stakeholders are shifting from traditional research centred interest (e.g. WAMS hosted by academia) to communities, labour unions, activists, non-profit - and non-governmental organisations. The customer need and stakeholder requirements stressed the importance of appropriate atmospheric measurement station deployment.

Objective IV: Perform functional analysis for the design and establishment of WAMS

A functional tree was created that indicated the initial design requirements, physical evolution and establishment of WAMS as well as the continual operational rationale. However, a need exists for an improved detailed management system that would result in enhanced planning, costing and sustained management.

Objective V: Explore the physical architectures and interfaces in the newly established WAMS

Physical and implementation architectures were investigated. A diagram depicts the most prominent interfaces, indicating that the WAMS is clearly a system-of-systems. However, due to constraints of time and space these individual systems could not be fully investigated. It was found that an integrated approach would be needed to investigate and link the management, financial and technical systems.

Objective VI: Test the design by calculating the operational availability of the system

A fault tree diagram was created that depicted the logical serial and parallel paths of the physical WAMS system. The operational availability of the gas and aerosol systems were calculated to be 88.5% each and 89.6% for the meteorological system. This was in good agreement with the ~94% data availability. Different methods of testing and evaluating the success of the various system architectures exist, in addition some methods of testing may prove more suited than others, and therefore a thorough understanding of the SOI is required when performing assessment.

4.2 Future perspectives

Systems Engineering tools and methods are comprehensive. Although the basic high-level methods and systems thinking were applied in this dissertation, it was found that each one of these methods could be expanded on vastly. Unfortunately, due to the limit of time, space and scope of the dissertation this could not be done. However, the author wishes that complete articles be written on the application of specific System Engineering methods with regards to the principals and methods of atmospheric measurements and monitoring. The focus in SA should therefore not be limited to the building of atmospheric measurement stations, but to educate the community on the tools and techniques available. When executed appropriately, these projects will become more manageable and deliver higher returns on investment. Perhaps this dissertation could spark the interest.

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