The Readiness of Systems Engineering at a South African Engineering Organisation

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Abstract. The purpose of this study is to explore and gain a broad perspective on the systems engineering methods currently employed at a South African research council. The aim is to question if these methods are ideal by comparing them with their alternatives. This paper focuses on the systems engineering methods used within the various competency areas of one of the engineering business units. The suitability of these methods for the nature of work being done in the respective competency areas is also explored. Systems Engineering Management Base Theory (SEMBASE) is used as a framework to find the gaps in each competency area and conclude possible ways of improvement thereof. A qualitative research method is used for this study. The data and information received from the interviews are analysed for emerging patterns that will confirm the theory. The findings show that the competency area focusing on Systems Engineering and Enterprise Architecture is adequately aware of the systems engineering processes and is well-equipped with its tools. The research also reveals that the Technical Competency Areas are not always aware of all the systems engineering processes and lack certain systems engineering tools. Some competency areas are indirectly using Systems Engineering but are unaware of it. More training and awareness is required to fill these gaps amongst the Technical Competency Areas.

Introduction and Background

The Council of Scientific and Industrial Research (CSIR) supports innovation in South Africa to improve national competitiveness in the global economy. Science and technology solutions and services are offered in support of several stakeholders, and prospects are recognised where novel technologies can be developed further and exploited in the public and private sectors for the social and commercial benefit (CSIR 2010).

The CSIR's mandate is as stipulated in the Scientific Research Council Act (Act 46 of 1988, as amended by Act 71 of 1990), section 3: Objects of CSIR (CSIR 2007):
"The objects of the CSIR are, through directed and particularly multi-disciplinary research and technological innovation, to foster, in the national interest and in fields which in its opinion should receive preference, industrial and scientific development, either by itself or in cooperation with principals from the private or public sectors, and thereby to contribute to the improvement of the quality of life of the people of the Republic, and to perform any other functions that may be assigned to the CSIR by or under this Act" (CSIR 2007).

To run such an organisation and successfully implement projects that require multidisciplinary teams, Systems Engineering is required. Systems Engineering is a field that focuses on the design and application of the entire system. It is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system (Haskins 2010). It involves viewing a problem in its entirety, considering various variables and facets, and relating the social to the technical aspects (Haskins 2010).

Problem Statement and Project Objectives

Problem Statement

The purpose of this study is to gain insight into the current systems engineering methods being used at the CSIR, with the aim of validating its suitability by comparing them with its alternatives.

Objectives

This paper focuses on the systems engineering methods used within the various competency areas of a CSIR engineering business unit. The suitability of these methods for the nature of work being done in the respective competency areas is also explored. SEMBASE is used as a framework to find gaps in the competency areas and recommend possible interventions thereof.

Scope of the study

The CSIR functions as an organisation with a number of semi-autonomous Operating/Business Units and National Research Centers focused on industry sectors. For this project, the scope is limited to one CSIR engineering business unit. The engineering business unit is further divided into seven subsections referred to as competency areas. The Integrated Competency Area mainly focuses on Systems Engineering & Enterprise Architecture and is subcontracted by the other 6 Technical Competency Areas as shown in Figure 1.
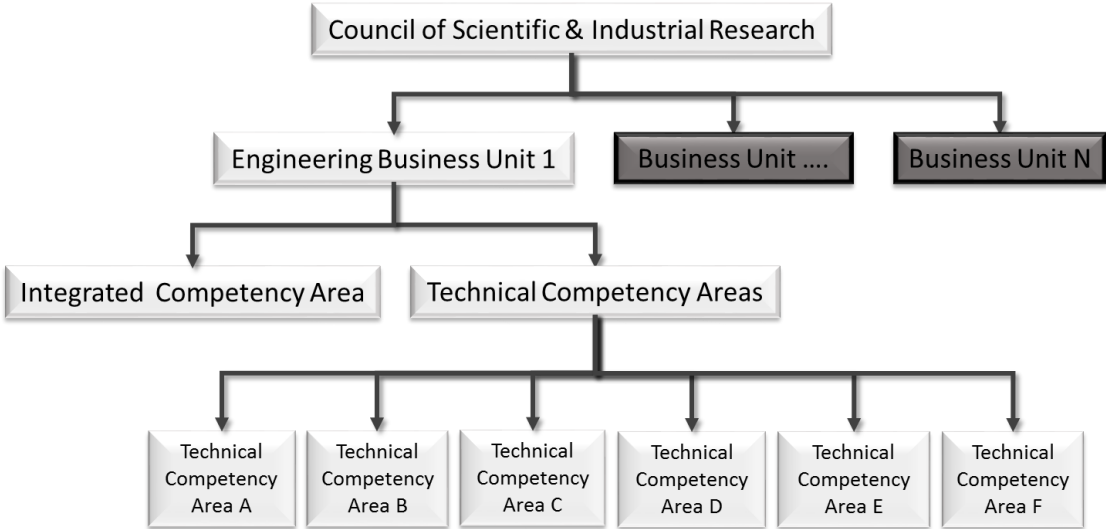

Figure 1. The CSIR Hierarchy

It should be noted that the conclusions may not be extrapolated for use in other business units within the CSIR or external to the organisation.

Definitions

The definitions of Systems Engineering is usually based on the background and experience of the individual or the performing organisation. A well-known definition published by the International Council on Systems Engineering (INCOSE) is (Haskins 2010):

"Systems Engineering is an interdisciplinary approach and means to enable the realisation of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs" (Haskins 2010).

Systems Engineering Standards

The standards used in Systems Engineering offer guidance to the systems engineer. Several domain-specific fields (e.g. communications, computers) specify detailed standards that also propose to manufacturers of software and hardware how compatibility with each other's tools may be achieved (Eisner 2002). Some standards that are operational at overall systems engineering activities level are listed below, with the last 3 discussed in this paper:

- DoD MIL - STD499B: Systems Engineering
- ISO - 15288 Systems Engineering Process
- EIA - 632: Processes for a Systems Engineering
- Capability Maturity Model Integration (CMMI Institute 2015)
- Systems Engineering Capability Assessment Model (INCOSE 1996)
- Blanchard's Systems Engineering Management Model (Blanchard and Fabrycky 2006)
- IEEE - 1220: Systems Engineering Process
- SEMBASE Model (Erasmus and Doeben-Henisch 2011a)

SEMBASE

SEMBASE is a model which attempts to formalise some important aspects of Systems Engineering Management (SEM) as illustrated in Figure 2. The development of the theory begins with the life cycle process, the formalisation of which can be achieved using a mapping, where an output is related to an input through a function without explicitly stating which mechanisms were used to obtain the output.
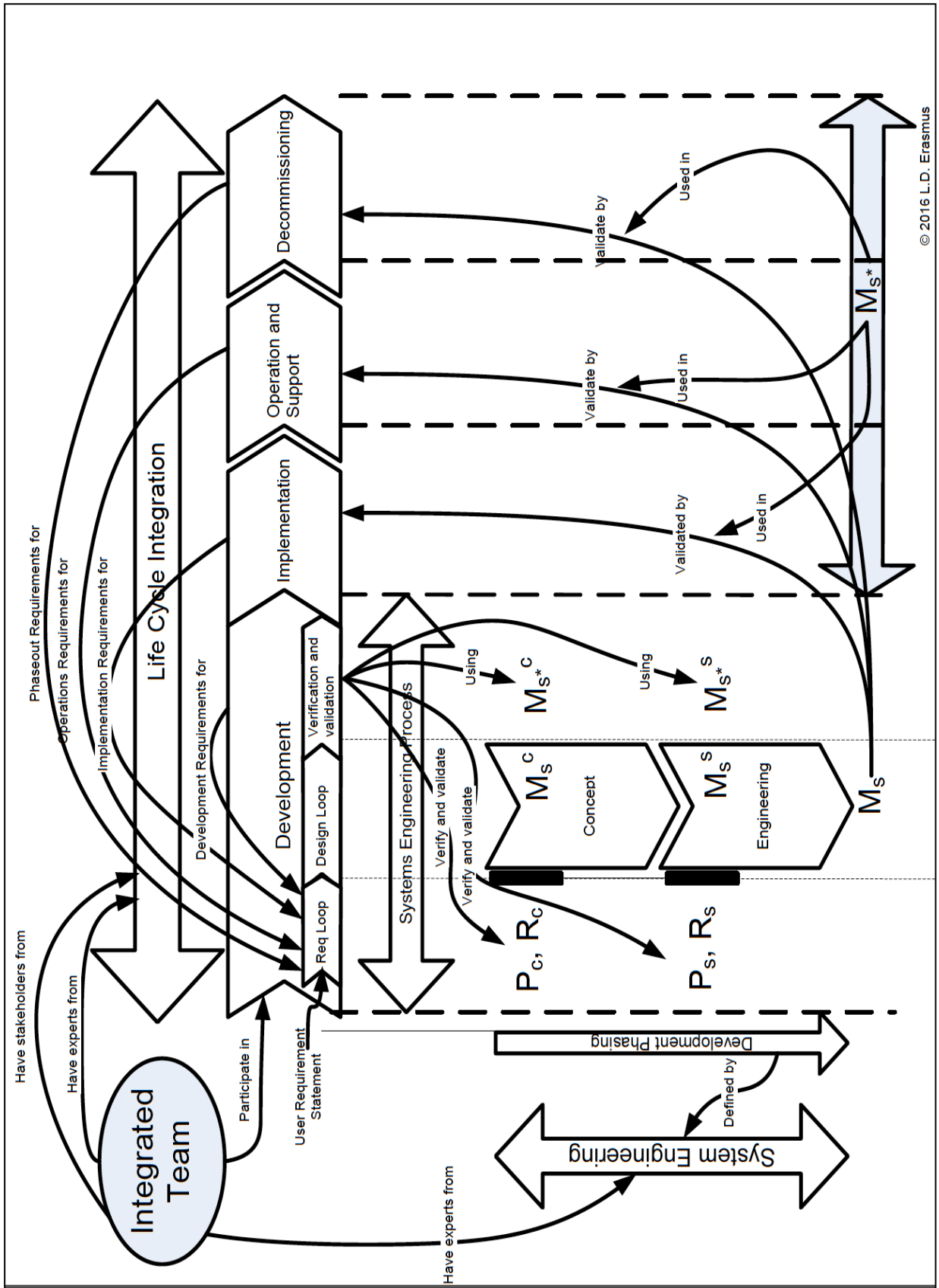
Figure 2. Illustration of a System-Engineering Management Base Theory (SEMBASE)
(Erasmus and Doeben-Henisch 2011b)

Gap Analysis between SEMBASE, IEEE, and Blanchard's SEM Model

In table 1, a gap analysis is shown between SEMBASE, IEEE 1220 and Blanchard's SEM Model. SEMBASE is established on numerous system engineering guides, standards and books. As a result, most of the important SEM activities are included in SEMBASE. A key aspect in SEMBASE is that in the lifecycle process people are considered as actors. Comparatively, IEEE 1220 standard, Blanchard's SEM model does not discuss this very clearly. Although SEMBASE is based on IEEE 1220 and other SEM models, it can also be noted that a Test and Evaluation Master Plan (TEMP) is not explicitly addressed in it.

Table 1: Gap Analysis between SEMBASE, IEEE, and Blanchard's SEM Model (Nyareli 2012)

Major SEM Activities	SEMBASE	IEEE 1220	Blanchard
Lifecycle integration	Involves the client and direct stakeholders in the designing process	Integration of concurrent design of products with their related life cycle processes	Not addressed
Phasing of Development	Controls the system design process & defines baselines	Controls the system design process & defines baselines	Controls the system design process & defines baselines
Applying Systems Engineering Process (SEP)	Applies SEP iteratively within life cycle stages	Applies SEP iteratively within life cycle stages	Applies SEP iteratively within life cycle stages
Development and production models	Uses models "to verify downstream information against upstream information"	Uses models " to verify downstream information against upstream information"	Not addressed
Integrated teaming	Responsible for producing a design solution that satisfies originating requirements and communicates that design to all stakeholders	Responsible for developing and satisfying the specifications and baselines associated with the element	Responsible for producing a design solution that satisfies originating requirements and communicates that design to all stakeholders
Engineering plan	Establishes System Engineering Management Plan (SEMP)	Establishes SEMP, TEMP master schedule, detailed schedule	Establishes SEMP, TEMP master schedule, detailed schedule, WBS, SOW
Technical reviews	Verification and validation	Includes design reviews and audits	Verification and validation

Research Design and Methodology

Qualitative research is a category of scientific research consisting of an investigation which (Mack et al. 2005):

- Searches for answers to a question;
- Systematically uses a predefined set of procedures to answer the question;
- Gathers data and evidence;
- Generates findings that were not already determined; and
- Generates findings that can further the research beyond the immediate boundaries of the study.

Qualitative methods are typically more flexible than quantitative research methods. They permit more impulsiveness and adaptation of the interaction amongst the study participant and the researcher. For instance, qualitative methods query typically using "open-ended" questions that are not always phrased in exactly the same manner with each respondent. With open-ended questions, respondents are permitted to answer in their own words, and these answers are likely to be more complex than merely a "yes or no" answer (Mack et al. 2005).

Additionally, with qualitative methods, the participant and researcher relationship is usually more casual than in quantitative research. Respondents get an opportunity to elaborate their answers and give more detail. In turn, the researcher gets a chance to respond to what the participants say immediately by tailoring the following questions based on the information provided by the respondent (Mack et al. 2005).

For the purpose of this paper, qualitative research methods are used. The data and the information received from the interviews as well as documentation provided as evidence are analysed.

Data Collection Strategy:
1. Interview Strategy;
2. Qualitative method; and
3. Secondary data (documentation) analysis – This was collected but not presented in this paper.

Interviews

The research data collection method focused on gathering information and data from the Competency Area Managers (CAMs), Research Group Leaders (RGLs) and systems engineers and their experiences at the CSIR. In order to accomplish the objectives of this study, the CAMs, RGLs and systems engineers were interviewed in a semi-structured approach.

The data collected from the interviews are treated as confidential, as such the name of the competency areas and the interviewees remain anonymous. All but one of the interviews were conducted in a one-to-one, semi-structured interviews, and each session lasted approximately 1 hour. The remaining one interview was conducted with two interviewees responding in the same interview.

Sampling Techniques:
1. Competency Area Managers of each competency area.
2. Research Group Leaders of each competency area.
3. Systems Engineers from each competency area.

Total research sample = 30 interviews from the various competency areas at an engineering business unit at CSIR.

A total of 32 members were interviewed, of which 2 of the recordings were inaudible, thus 30 were taken into account for the purpose of this paper.

Data Gathering Process

Ten main research questions were asked; sub-questions were asked for completion if not addressed by the main research question. All the interviews were conducted at the CSIR premises (Pretoria campus), at the interviewee's offices. All participants in the interviews were either directly involved in Systems Engineering or lead/manage a team that is/was involved with Systems Engineering.

The interviews included respondents from all competency areas in the applicable business unit of the CSIR in Pretoria. The respondents were selected by the researcher taking into account their involvement in Systems Engineering as well as their availability. Each interview was recorded for reference, with the permission of the interviewee, in line with the ethics clearance for this study.

Results

For the purpose of simplicity, the competency areas are categorised as below:
- Integrative Competency Area: comprises of a group of people who perform Systems Engineering and Enterprise Architecture.
- Technical Competency Area: consists of discipline-specific engineers and scientists developing various products.

Qualitative Discussion of Research Results

The interviews were done in the nature of a narrative enquiry. The open-ended interview questions were not all necessarily asked in the identical order as it appears in this paper. Some of these interview questions were rearticulated and used as follow-up questions if not addressed by the interviewees while answering the main question. Other important information was also captured during the conversations with these interviewees.

In general, the questions in the interview addressed the systems engineering methods used in the business unit. The questions asked and interviewees' response summaries are discussed below.

Question 1:
- *Can you tell me how you set/treat your user requirements?*
- *How do you ensure that the system meets these requirements and user needs?*

The user/stakeholder approaches the CSIR with a problem and requests a user requirement specification document during the requirement elicitation session. Once this is agreed upon by all stakeholders of the project, a proposal is sent to the user/stakeholders for approval.

To ensure that the system meets its requirements, test and evaluation are done on the sub-systems. Validation and verification are done on real life operational scenarios to ensure that the system operates as expected.

It was seen that the majority of members follow the correct systems engineering method to set user requirements. However, it was noted that the Integrative Competency Area, in general, focused more on traceability as compared to the Technical Competency Areas. Validation & verification was considered important across all competency areas.

Question 2:
- *Please tell me a little bit on how do you do acquisition and implementation.*
- *What were the factors that have hindered the process of implementation?*

In the Integrative Competency Area, implementation usually implies conceptualization phase. The systems engineers use commercial requirements management tools for the implementation of the functional requirements and implement the architecture of the project during this phase.

At the Technical Competency Areas, however, implementation refers to the implementation of the actual project.

The factors that hinder the process of implementation were noted to be similar across all competency areas. This included issues like incorrect technology choices, internal disputes, bias towards an idea, change in requirements etc.

Question 3:
- *Can you tell me how you plan your project?*
- *Which templates or guidelines did you use?*

The Integrative Competency Area is comparatively more structured than the Technical Competency Area in terms of systems engineering planning. The project managers and systems engineers work closely with each other to manage a project. The communication link between them is the SEMP and the link between the project manager, client, and the rest of the team is a project plan.

Firstly, a requirement elicitation and a concept of operations (CONOPS) document is created. From the CONOPS, a SEMP is derived, which gives a technical approach on how to solve the problem. The project manager translates this into a project plan which includes financial and timeline issues.

In the Technical Competency Areas, however, not all projects have a SEMP. This is dependent on the scale of the projects. Usually smaller projects don't employ such methods due to the financial and time limits. In these cases, the User Requirement Specification (URS) is agreed upon, and a project plan is created without a need for SEMP.

Some interviewees mentioned the lack of available templates. While each problem is different and requires a different way of engineering a solution, a standard template may help in saving the time and effort required to document the required information.

Question 4:
- *Can you please tell me how you do phasing on your project and what you address in each phase?*

Phasing is done on projects to ensure that there are funds available to continue with the next phase of the project. Each phase is completed and submitted to the client and payment is made per milestone. For smaller projects, the entire project is completed in one phase and has only one deliverable. Phasing is generally incorporated in larger projects

At the Integrative Competency Area, phasing is derived from the SEMP. They key diagram in the SEMP is the Systems Engineering Management Schedule (SEMS). The phases are the key milestones/deliverables of the project, derived from the SEMS and shown in the project plan.

The phases depend on the nature of project but usually include the lifecycle stages of a project.

Question 5:
- *Can you tell me how you manage the risks (technical and program) for performance, cost, and schedule in one of your projects?*
- *Did you have written procedures to do that? Have you used any standards?*

At the Integrative Competency Area, a risk register is used to keep track of and manage known risks. It is a live document and is usually available to all the team members to log their risks. The systems engineer and project manager check the risk register weekly and try to mitigate risks as they are indicated.

At other competency areas, risk registers are managed per competency area instead of per project. This is due to the size and nature of projects done in those competency areas.

A general pattern noted about risk management was that no competency area uses a specific standard or other published methods to mitigate risks. Most systems engineers mentioned that they use a paragraph to describe the risks in the SEMP or project plan. They are only aware of the vague mentioning of it in the INCOSE Systems Engineering Handbook or the ISO-15288 Systems Engineering Process. However, from research, it was found that there is a standard namely ISO 31000 that provides principles and generic guidelines on how to manage and mitigate risks on projects. The risk management family of standards includes ("International Organization for Standardization" 2016):
- ISO 31000: Principles and guidelines on implementation;
- ISO/IEC 31010: Risk Management – Risk Assessment Techniques; and
- ISO Guide 73: Risk Management – Vocabulary.

Question 6:
- *Can you tell me how you manage all the data and information on your projects?*
- *How secure is it?*

To manage the documents on projects, configuration management systems are used across the business unit. Backups are made on internal servers owned by or shared amongst competency areas. It is reasonably secured with digital encryption, however, only confidential or open information is stored on the servers. Other classified documents such restricted, secret and top secret are not stored on the servers as they require immense security.

There have been no major problems with leaked information or data lost at this engineering business unit. A few small cases included lost laptops/hard drives or corrupted drives. Most data was however recovered in each of the cases as it is usually backed up.

Question 7:
- *On you projects, can you tell me where you are under-staffed or did not have the necessary skills? In a case where there were not enough skills, can you tell me how you handled that?*
- *What are the key skill shortages identified in this competency area and what measures have been taken to address the issues?*

Being understaffed is a common issue in the business unit. In most cases, the resources available are stretched as much as possible. This engineering business unit covers a wide variety of skills, hence, work is subcontracted to other competency areas within this business unit or even to the other business units at CSIR with the relevant skills when necessary. If the required skills are not available at CSIR, work is subcontracted to external companies. It is often difficult to employ new staff members due to the business situation (factors including cash flow, time constraints etc.).

A lack of experienced systems engineers has been noted throughout the entire business unit. The business unit lacks systems engineers with sufficient lifecycle skills – that have experience in the entire lifecycle of a system. Systems engineers with domain experience are also very uncommon. It is extremely important to have technical and domain-specific knowledge and experience to become a good systems engineer, instead of blindly following the textbook methods.

Question 8:
- *Can you tell me how you do the integration of your essential disciplines?*
- *What challenges did you observe during the integration of these disciplines and how did you tackle them?*

As a systems engineer, it is very important to have domain experience. Once a person has worked in and mastered a certain domain, he/she can see what value everyone adds to the project. Usually, the project architecture gives a broader overview, from which the skills required can be determined.

One of the main issues with integration between subsystems is that planning is not done from the beginning. People often underestimate the integration period and leave it to last minute. The best way to prevent this is to start integration from the first day. To tackle this problem, allocate enough time for integration so if there are any problems, there's enough time to redesign or fix the issues.

Question 9:
- *Please tell me how you've used interdisciplinary teams during the development of system requirements.*

When working in a multidisciplinary team, it is very important that everyone in the team understands the objectives of the project. The SEMP document is reviewed with at least the interdisciplinary team leaders until everyone has consensus before it is registered.

Reviewing of the key documents like the SEMP, project management plan, the quality plan, the conflict plan, design rules, templates etc. needs to be reviewed and tailored with the team before starting the project. This improves the ability of the team to work together.

Question 10:
- *Considering the customer's feedback, how would you rate the project success based on the following aspects?*
  - o   *Client's need*
  - o   *Schedule*
  - o   *Cost*
  - o   *After-sales support*
  - o   *Other aspects*

In general, the client's needs are the priority of any project at this engineering business unit. There is always a tradeoff between schedule and cost, depending on what is more important, the other can be given some leeway. After-sales support is not applicable in most cases at this engineering business unit.

Conclusion & Recommendations

Based on this research, it is evident that systems engineering processes are being applied at the engineering business unit in question at the CSIR. The main findings of this research are that Integrated Competency Area is aware of Systems Engineering and is well-equipped with its tools. However, in the Technical Competency Areas, there is room for improvement. In many cases, the interviewees mentioned that they do not employ Systems Engineering, which was a contradiction to their responses to the open-ended interview questions. The research reveals that the Technical Competency Areas are not always aware of the systems engineering processes and lack certain systems engineering tools.

It was also mentioned that there is a lack of templates available. While each problem is different and requires a different way of engineering a solution, a standard template may help in saving the time and effort required to document the necessary information.

From this research, it is recommended that especially the Technical Competency Areas be further trained on systems engineering processes, how to apply it and how it can benefit them. More training and awareness is required to fill these gaps amongst the Technical Competency Areas.

Acknowledgements

A special thanks to all the personnel at this engineering business unit, at the CSIR, that supported this research.

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Biography

Humna Hassan Malik obtained her BIng Electrical & Electronic Engineering (2014) and BSc Information Technology (2014) degrees from the University of Johannesburg. She is currently pursuing a MEng Engineering Management with specialisation in Systems Engineering, also from the University of Johannesburg. She started working at the CSIR as a bursar in 2013, and is currently affiliated with the CSIR as a master's student and is being trained towards becoming a Systems Engineer in future.

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