Qualitative exploration into the application of Systems Engineering within a South African science council

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***Abstract*—A description is provided on how good systems engineering processes and methods are used so that gaps can be determined by quantitative methods for informing training programs. The Systems Engineering Capability Model (SECM) is used to determine how good systems engineering methods and processes are performed implicitly and explicitly as well as indicating the gaps. This study focuses on the systems engineering methods currently being used within one of the engineering business unit at a research council. Gaps between the current practices in competency areas are identified for consideration of possible interventions. Qualitative method where empirical data was collected through interviews and transcribed, is processed with an appropriate qualitative tool. This research shows that the Integrative Competency Area (ICA) knows the processes and use them well. In the Technical Competency Areas (TCA) some people use it implicitly, while others do not know about it. There is a general request for making processes, templates more readily available for people to use inside the organization. This research shows the gaps that can be addressed through the designing of training programs within the organization. This research could be extended to study other areas within the science council as well as other organizations.**

Keywords*— *Systems Engineering, Systems Engineering Management, Capability Model

I. Introduction

"Systems engineering is a waste of time" [1], [2] is a regular phrase heard from engineers and managers in South African industry.

A narrative enquiry was conducted within an engineering business unit of a science council found under the legislation in South Africa. It was found that Systems engineering is not well understood in amongst the discipline specific engineers.

This research council dedicates its time and effort to support multidisciplinary innovations in South Africa to increase their competitiveness in the international economy. To run an institute such as this research council and to successfully implement projects that require multidisciplinary teams, systems engineering is required. The field of Systems Engineering focuses on design as well as the application of the complete system, it is a holistic approach [6], [7]. It is an iterative process which includes a top-down synthesis, development as well as real-world system operations which satisfy the requirements for the system in an optimal manner [8]. It includes viewing the problem in its entirety, considering the various variables and facets and linking the social and technical aspects [8]. Systems engineering is not just a set of rules that are slavishly applied but more about a way of thinking and attitude that is an extension of much of conventional engineering design practice [9]. Systems engineering deals with the total system and its complete lifecycle [10].

A. *Problem Statement*

The main purpose of this study is to gain a deeper insight into the current systems engineering methods being used at this research council and to question if they are ideal by comparing them with international standards. This study focuses on the systems engineering methods currently being used within one of the engineering business unit at this research council.

This study focuses on the systems engineering methods used within the various competency areas at DPSS and the suitability of these methods for the kind of work being done in the respective competency areas. A Theory for Systems Engineering Management (SEMBASE) [21] is used as a baseline framework to compare different systems engineering standards with one another. Gaps between the current practices in competency areas are identified for consideration of possible interventions.

B. *Research Objective*

The aim of this study is to explore the implicit and explicit systems engineering methods currently being practised at engineering business unit. These are studied thoroughly which conclude to the suitability of these methods for the kind of work being done in the respective competency areas. Should the methods currently being used not be the most applicable method, it will be identified.

The research questions are:

1. Does this engineering business unit use Systems Engineering methods?
2. Are the Systems Engineering processes used at this engineering business unit effective?
3. What are the gaps?

The propositions supporting these research questions are:

1. This engineering business unit uses Systems Engineering methods.
2. This engineering business unit implements Systems Engineering methods well.
3. People are aware of Systems Engineering methods at this engineering business unit.

The motivation for this paper is to further investigate in more detail how good Systems engineering processes are used within the above-mentioned engineering business unit. This paper validates the results obtained in [1].

This study focuses on one of the engineering business unit at the research council. Therefore, it should be noted that the results and conclusions may not be generalized for use in other engineering business units within the CSIR nor any external to the organizations.

C. Rationale of the research study

The main purpose of any business is to make money by selling its products and/or services. Due to an increase in the level of technology of engineered systems and a higher level of system complexity, an increase in the systems engineering activities is required [11]. The field of systems engineering has evolved to aid organizations in overcoming the challenges of today [12]. Systems engineering allows an organization to understand the problem; enables it to find the best possible solution; then offers support in building, integrating, testing, operating, and maintaining the solution within the budget and time constraints [12]. Systems modelling is not considered as merely a "good idea" anymore, but it's become a vital part of any project of a sizable scale [13].

D. Importance of the research problem

Systems engineering is a very useful tool to assist with the smooth operation of big projects in an environment similar to that of this engineering business unit. The gaps identified from this study will help in the identification of intervention opportunities in improving the awareness of Systems Engineering at this engineering business unit. It will also expand the skill set of the relevant this engineering business unit personnel and help them to be able to deliver and function better in multidisciplinary teams to execute the research council's mandate.

If this gap is not resolved, the addressing of more complicated problems, and even complex problems, it will make this engineering business irrelevant. The results of this paper can be used to inform the design of a training program for the engineering business unit.

A literature review will be discussed next around SE and systems engineering management. A qualitative methodology is then used in addressing the problem using SECM as the reference framework. The analysis was done using a tool for processing qualitative data. This is followed by the qualitative results, a discussion and a conclusion.

II. Literature Review

Systems engineering is an interdisciplinary approach for realising successful systems. Its main focus is to satisfy customer's need, by defining the customer's needs and functionality that is required, which is followed by the design synthesis and system validation, taking into account the entire problem throughout the lifecycle [8]. It takes into consideration both the business as well as the technical needs of the clients with the objective of never compromising on the quality of the product [8] It also includes defining and managing the system configurations, translating the definition of the system into WBS and developing the evidence to make management decisions [14]. This approach is repeatedly and recursively applied throughout the lifecycle to improve the quality of the end product [15].

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 [16]. Standards discussed in this study that are applicable at the level of the overall systems engineering activities [17] are listed below.

- IEEE Std 1220-2005: IEEE Standard for application and management of the systems engineering process [18]
- ISO/IEC Std 15288-2008: Systems and software engineering – System life cycle process [19]
- Blanchard's Systems Engineering Management Model [20]
- SEMBASE Model [21]
- EIA-731.1: Systems engineering capability model [22]
- EIA-731.2: Systems engineering capability model appraisal method [23]

A. Gap Analysis between SEMBASE, IEEE Std 1220, Blanchard's SEM Model & EIA-731.1

A detailed gap analysis is done between SEMBASE, IEEE Std 1220, Blanchard's SEM Model and EIA-731.1 in [1], [2]. It shows that SEMBASE is established on numerous system engineering guides, standards and books. Thus, 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 Std 1220 standard, Blanchard's SEM model and EIA 731.1 does not discuss this very clearly. Although SEMBASE is based on IEEE Std 1220 and other SEM models, it can also be noted that a Test and Evaluation Master Plan (TEMP) is not explicitly addressed in it.

EIA SECM was chosen for this study as it is more applicable and it covers more areas relevant to this study. This concept model is derived from EIA-731.1 [22] and EIA-731.2 [23] and is further discussed in below.

B. *EIA-731.1 Systems Engineering Capability Model (SECM)* [22]

The Systems Engineering Capability Model (SECM) EIA-731.1 is an instrument that can be used to assess the capability of the current Systems Engineering processes at an organisation. The SECM also offers a framework that can guide the development or improvement of these Systems Engineering processes [24]. EIA-731.1 is defined to aid an extensive range of activities for improvement, which includes process design, process improvement and appraisals [22].

The standard, with the title ''Systems Engineering Capability Model' or SECM,' has been promulgated by the Electronic Industries Association [22]. The main objective of EIA-731.1 is to aid systems engineering capability development and improvement of [22]. EIA-731.1 take into account all the activities that enable or are associated with systems engineering. Systems engineering is an interdisciplinary approach and a way to allow for realising successful systems. In EIA-731.1, systems engineering not only limits to what Systems Engineers or Systems Engineering organisations. Instead it includes the interaction of processes, people, and organisations which leads to the execution of the necessary activities [22].

A proper use of EIA- 731.1 is intended to further enhance the capability of performing systems engineering using EIA-731.1. The enhanced capability allows an organisation to [22]:

- Decreased cycle time to deploy system products from concept phase;
- Improve the deployed system product capability match with the stakeholder requirements;
- Decrease the overall cost of ownership for system products;
- Decrease engineering changes;
- Enhance the quality of systems;
- Enhance the communication between the people engaged in the system;
- Increase the ability sustaining and upgrading system products once deployed; and
- Decrease risks during development.

EIA 731-1 should be used together with its appraisal method, EIA 731-2, which is discussed in section C, to develop, improve, and assess the capability of systems engineering [22].

C. *EIA- 731.2 systems engineering capability model appraisal method* [23]

A Systems Engineering Capability Model Appraisal is an assessment of the current systems processes for a business unit. This appraisal is established on responses received from the in-depth discussion with managers, systems engineers and other practitioners on the appraisal team's knowledge and experience [24]. The questions are based on the appraisal questionnaire guide as discussed in [23].

The main objectives of an appraisal are [23]:

- To identify the opportunities for improvement, grounded in areas with deficiency;
- To gain a buy-in from the organisation for change;
- To confirm the progress of process improvement and to define a new reference point or baseline in the subsequent appraisals.

III. Study Area

The study areas for this study are Systems Engineering, Systems Engineering Management. A theory for Systems Engineering Management known as SEMBASE is discussed below.

A. *SEMBASE Model [21]*

SEMBASE is a model which attempts to formalise some important aspects of systems engineering management. Figure 1 summarises the systems engineering process as presented in the paper titled "The readiness of Systems Engineering at a South African engineering organisation" by the researcher [1]. The development of the theory begins with the life cycle process, the formalisation of which can be achieved using mapping, where an output is related to an input through a function without explicitly stating which mechanisms were used to obtain the output [21].

Figure 1 shows that a SEMBASE model is built on various descriptions of the SEM models [21]. The SEM models perform the following major activities [21]: lifecycle integration, development phasing, and SEP. Lifecycle integration engage the stakeholders, including the clients in the design process whereby the client initiates the process with a Required Operational Capability (ROC) [21]. The ROC becomes part of the stakeholder documents of the operation and support stage requirements [21]. This ensures that the design solution is viable throughout the system life cycle as the stakeholder requirements are described in the applicable life cycle function document [21], [25].

Stakeholders responsible for all the product life cycle stages are represented early during the development of the system requirements. This enables concurrent engineering to be practised.

The "development phasing control the design process and defines baselines for coordinating the subsystems, disciplines and specialities design efforts". The development phases of this

SEM model are based on development phases described in [26]. These phases are comparable to the ones described by Blanchard in [20]. The concept stage discussed in ISO/IEC 15288 is also included in SEMBASE [21], [25].

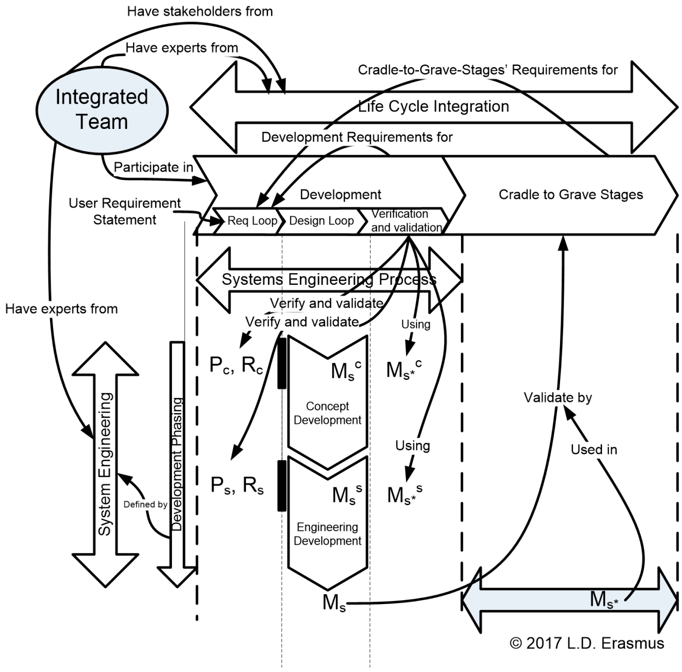

Figure 1: A Theory for Systems Engineering Management (SEMBASE) [21]**,** [1]

IV. Methodology

A qualitative research approach is used for this study because not all people are versed in Systems Engineering and the models thereof. The data and the information received from the interviews as well as documentation provided as evidence are analyzed, to test the derived scientific questions. This is done using a qualitative data analysis tool which uses concept tagging to come to a conclusion.

A. 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 this engineering business unit. To accomplish the objectives of this study, the CAMs, RGLs and systems engineers were interviewed in a semi-structured approach. All but one of the interviews were conducted in semi-structured, one-to-one interviews, and each interview lasted approximately 1 hour. The remaining one interview was conducted with two interviewees responding in the same interview.

B. Unit of analysis

The unit of analysis for this research study is an engineering business unit at the research council. This engineering business unit is further divided into 2 categories for the purpose of this study. These categories are Integrative Competency Area and Technical Competency Areas.

C. Sampling

Purposive sampling a nonprobability sample that follows to specific criteria [27]. It is a technique broadly used for qualitative research to indicate and select information-rich cases to use limited resources effectively [28]. A non-probability purposive sampling is used to draw representative samples for this study.

For the purpose of this research, the CAMS of all competency areas within this engineering business unit are selected by the researcher. They further recommended representatives for each competency area with Systems Engineering experience. It was up to the interviewees to decide whether or not to participate in the interviews.

A total of 37 members were interviewed from the various competency areas at this engineering business unit. Nine of these recordings were inaudible or had other technical issues, thus 28 were considered for this study.

D. Ethics of research

According to [29] and [30], ethics symbolises communal and individual codes of conduct established on the obedience of implicit or explicit principles. Ethics clearance for this study is granted by the University of Johannesburg. The data collected from the interviews is treated as confidential, hence the name of the competency areas or the interviewees remain anonymous.

E. 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 research council premises, 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 research council. The respondents were selected by the researcher considering 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.

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.

In some technical competency areas, there's only one respondent and it is not possible to fairly compare it to the integrative competency area. Therefore, all technical competency areas are grouped together to fairly compare it to the integrative competency area.

The open-ended questions for the interview weren't all necessarily asked in the identical order as presented in this study. A few of these interview questions were rearticulated and used as follow up questions if not already addressed by the interviewees while answering the main question. Additional important data was also captured during the dialogues with these interviewees. Overall, the questions in the interview addressed the systems engineering methods used in the business unit.

F. *Data Analysis Process*

The data obtained from the interviews is analysed using multiple ways of qualitative analysis. This includes:

1. Qualitative analysis tool (Atlas.ti) method; and
2. Secondary data (documentation) analysis.

1) Qualitative analysis tool (Atlas.ti) method

The interview was recorded with the permission of the interviewees. For Atlas.ti analysis, the recordings were transcribed word for word using an online software called 'Transcribe'. These were then coded or tagged using the Key Focus Areas that are discussed in SECM [1][2][22] and are used as guidance to tag the data. The frequency of tags indicate how often each Key Focus Area is used.

2) Secondary data (documentation) analysis

Project documentation was collected as evidence to validate what the interviewees stated. These documents are represented, analysed and summarised in [2].

V. Results

Capability levels measure the capability of the business units in an organization [22], [23]. Table 1 shows the correlation between the average number of tags per interview and the capability levels. These formulae were formulated to represent the data obtained from the interviews onto the capability levels appraisal charts.

The total number tags of Key Focus Areas per competency area is tabulated in Table 2 and Table 3. The average tag for each Key Focus Areas per interview is calculated. If the average number of tags is less than 0.5 tags per interview, the capability level allocated is 0 (initial). Similarly, if the average number of tags is greater than or equal to 0.5 but less than 1 tag per interview, the capability level allocated is 1 (performed). A same applies for the remaining levels, as shown in the table below.

Table 1. Capability level score for tags per interview

Capability Levels		Capability level score for average number of tags per interview
0	Initial	$x < 0.5$
1	Performed	$0.5 \geq x < 1$
2	Managed	$1 \geq x < 1.5$
3	Defined	$1.5 \geq x < 2$
4	Measured	$2 \geq x < 2.5$
5	Optimized	$x \geq 2.5$

Table 2 and Table 3 are based on the appraisal chart for the Systems Engineering technical, management and environment categories as discussed in EIA-731.1 [22] and EIA-731.2 [23].

Table 2 illustrates the data gathered from the interviews at the Integrative Competency Area. The total number of Key Focus Area tags picked up from the interviews are shown in this table. The average number of tags per interview is calculated and a capability score is allocated to each Key Focus Area for the Integrative Competency Area based on Table 1.

Table 2. Data gathered from Integrative Competency Area

No	Key Focus Area	Total number of tags	Average number of tags per interview	Capability level score
1	**Systems Engineering Technical Category**			
1.1	Define Stakeholder and System Level Requirements	33	2.5	5
1.2	Define Technical Problem	23	1.8	3
1.3	Define Solution	23	1.8	3
1.4	Assess and Select	23	1.8	3
1.5	Integrate System	30	2.3	4
1.6	Verify System	36	2.8	5
1.7	Validate System	36	2.8	5
2	**Systems Engineering Management Category**			
2.1	Plan and Organize	30	2.3	4
2.2	Monitor and Control	17	1.3	2
2.3	Integrate Disciplines	30	2.3	4
2.4	Coordinate with Suppliers	3	0.3	0
2.5	Manage Risk	20	1.5	3
2.6	Manage Data	13	1.0	2
2.7	Manage Configurations	13	1.0	2
2.8	Ensure Quality	26	2.0	4
3	**Systems Engineering Environment Category**			
3.1	Define and Improve the Systems Engineering Process	26	2.0	4
3.2	Manage Competency	7	0.5	1
3.3	Manage Technology	14	1.0	2
3.4	Manage Systems Engineering Support Environment	23	1.8	3

From Table 2, majority of the Key Focus Areas scored high on the capability level appraisal chart. ICA is excellent at defining stakeholder and system level requirement, verification and validation. This was expected as the Integrative Competency Area focuses a lot on the systems engineering processes. ICA is also doing well with integrating systems, planning and organizing, ensuring the quality of work they produce and defining and improving the systems engineering process.

ICA, however, scored very low on coordinating with suppliers. One reason for that could be that there were no questions directly focusing on coordinating with suppliers. Another reason could be that since most of the work done at ICA is in the conceptual phase, interaction with the suppliers is not necessary.

Table 3 is like Table 2 but it illustrates the data gathered from the Technical Competency Areas. The average number of tags per interview is calculated and a capability score is allocated to each Key Focus Area for the Integrative Competency Area.

Table 3. Data gathered from Technical Competency Areas

No	**Key Focus Area**	**Total number of tags**	**Average number of tags per interview**	**Capability level score**
1	**Systems Engineering Technical Category**			
1.1	Define Stakeholder and System Level Requirements	26	1.9	3
1.2	Define Technical Problem	10	0.7	1
1.3	Define Solution	10	0.7	1
1.4	Assess and Select	14	1.0	2
1.5	Integrate System	12	0.9	1
1.6	Verify System	16	1.1	2
1.7	Validate System	18	1.3	2
2	**Systems Engineering Management Category**			
2.1	Plan and Organize	24	1.7	3
2.2	Monitor and Control	5	0.4	0
2.3	Integrate Disciplines	22	1.6	3
2.4	Coordinate with Suppliers	2	0.1	0
2.5	Manage Risk	18	1.3	2
2.6	Manage Data	14	1.0	2
2.7	Manage Configurations	16	1.1	2
2.8	Ensure Quality	12	0.9	1
3	**Systems Engineering Environment Category**			
3.1	Define and Improve the Systems Engineering Process	4	0.3	0
3.2	Manage Competency	14	1.0	2
3.3	Manage Technology	33	2.5	5
3.4	Manage Systems Engineering Support Environment	2	0.1	0

Table 3 show that the Key Focus Areas scored relatively low on the capability level chart. It scores high on managing technology, which is expected since TCA specializes in more technical fields as compared to ICA. It is interesting to note that TCA scores extremely low on monitor and control and coordinating with suppliers. This goes intuition but an explanation for this is that people often forget to include suppliers in their planning phase.

TCA also scored quite low on defining and improving the systems engineering process and managing systems engineering support environment. Once again, this is expected from TCA as its main focus is not on systems engineering.

VI. Analysis

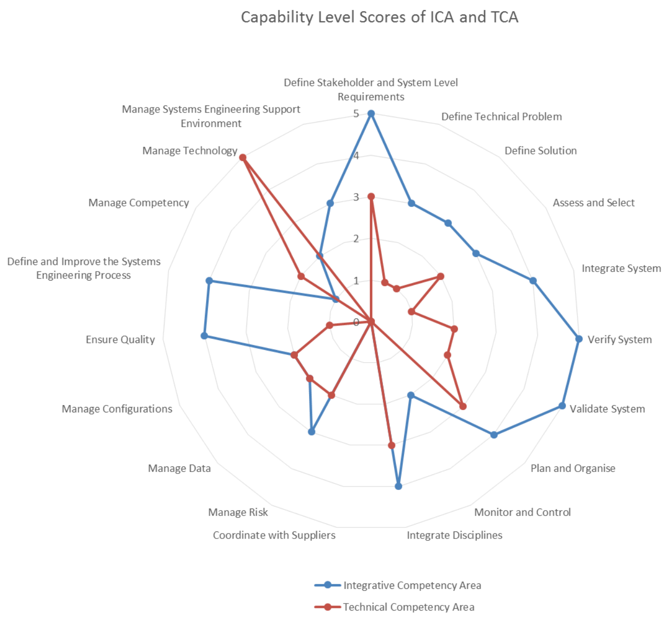

Figure 2. Capability Level Score of ICA and TCA

Figure 2 shows a radar plot of the data presented in Table 2 and Table 3. This graph clearly shows that there is a huge gap between the two categories of competency area categories. It is also interesting to note that the overall pattern is very similar between the two groups with ICA leading in the scoring.

It is clear from this table that Integrative Competency Area is applying Systems Engineering processes better than the Technical Competency Area.

However, it can be noted that the Technical Competency Area is doing far better at managing technology. This was expected as the Integrative Competency Area usually integrates the projects that the Technical Competency Areas worked on. The Technical Competency Area is also doing better at managing competencies. Once again the credit goes to the kind of work being done at the Technical Competency Areas. The Integrative Competency Area does not develop any new technology.

It can be seen from this capability radar chart that there is comparatively a lot of room for improvement in TCA.

VII. Discussion

These research questions are researched and addressed by the data and evidence collected throughout this study. Based on this research, it is evident that systems engineering processes are being applied at the engineering business unit in question at the research council.

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. The results are presented separately for the two groups in the engineering business unit. Integrated Competency Area implements systems engineering methods very well. However, according to Figure 2, it is shown that Technical Competency Area can improve on the implementation of systems engineering processes.

A gap analysis was also done on the different systems engineering standards. There are gaps between SEMBASE, IEEE Std 1220, Blanchard's SEM Model and EIA-731.1. One major gap identified is that SEMBASE considers people as actors in the lifecycle process. Comparatively, IEEE Std 1220 standard, Blanchard's SEM model and EIA-731.1 does not discuss this very clearly. Although SEMBASE is based on IEEE Std 1220 and other SEM models, it can also be noted that a Test and Evaluation Master Plan (TEMP) is not explicitly addressed in it. A more detailed discussion can be found in section II.A.

VIII. Conclusion

From this research, ICA doesn't require any further training on Systems Engineering.

It is recommended that 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 and make them aware of the value of Systems Engineering.

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.

It can be recommended that this research should also be studied in other areas within the science council as well as other organizations to make it more universal.

After all, SE is useful, especially in the demand for templates and proper requirements and through the results where people are using it without even knowing it.

IX. Acknowledgment

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