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A framework for developing systems engineering management for process plant acquisition projects

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Abstract

South Africa has a history of poor performance on process plant acquisition projects in the process industry that apply chemical processes within large processing facilities to convert raw materials such as crude oil into fuel and by-products. The most recent failures include the highly publicized Medupi and Kusile projects. This research is based on the acquisition or expansion of large process plants within petrochemical, mining, and energy, typically Systems of Systems integration projects. A significant component of their failings can be attributed to poor systems engineering and systems engineering management capabilities. Acquisition in the context of this study refers to all processes within the stage-gate project development model from project inception to the beneficial operation of the acquired facility. Due to a lack of systems and tools to guide the development of systems engineers and systems engineering managers within the sector, this research was undertaken to develop an industry-specific framework based on the INCOSE framework to support development and recruitment processes. A conceptual model derived from a literature survey was validated and improved with qualitative data gathered using structured open-ended interviews with industry specialists and experts from organizations within the petrochemical, mining, and energy sectors. Insights regarding current recruitment practices and development processes were analyzed to validate the need for a tool and develop an appropriate model for its application. Finally, the analysis and general causes of project failures validated the contents of the framework by highlighting critical competencies and traits required to succeed within the sector.

KEYWORDS

complex projects, systems engineering, systems engineering management, systems engineering manager

1 | INTRODUCTION

The systems engineering manager (SEM), which is the final line of progression within the systems engineering (SE) field, directs the design, development, synthesis, and creation of a system based on customer needs, acting as a "chief designer" of the system rather than just being the system analyst.[1] Although research and development in the field of SE have improved our abilities in the interpretation, design, development, implementation, and management of single systems over the past 50 years, we still face significant challenges with the relatively new phenomenon of systems of systems engineering (SoSE), that is, the integration of multiple complex systems.[2]

Carlock and Fenton[3] highlighted that SE handbooks frequently describe the development of individual stand-alone systems, that is, systems that are identical and deployed similarly at any site location. In such instances, the user has little influence on the design and development of the system, for example, an aircraft. Developing systems of systems (SoS), particularly systems that involve integration with several existing (legacy) systems, is a far greater challenge than developing stand-alone systems. Each system has unique capabilities, constraints, budgets, schedules, and interface requirements that must be considered during development and integrated to work effectively as a synergistic whole. The SoS is generally a heterogeneous system, implying that each system or subsystem of the SoS is generally custom-built or developed to suit-specific site conditions of the regions in which they are deployed.[3]

Complexity is further exacerbated by the fact that the integrated SoS is a consolidation of independent systems developed by numerous organizations. Although substantial research has been undertaken to address risk, uncertainty, and schedule urgency, the complexity issue has received limited attention. This is surprising given the extreme demand for organizational capabilities required to manage complexity in the megaproject environment. In most instances, poor megaproject performance was attributed to a lack of prior organizational experience and capabilities.[4]

Most organizations manage the risk associated with acquiring such facilities by transferring the risk to an engineering consultant who acts for and on behalf of the owner. Irrespective of how the project is contracted, SEMs with robust systems thinking (ST) and SE capabilities are essential to facilitate the system interface integration management necessary to achieve the desired outcomes.

SEMs in this environment require broad-based interdisciplinary and multidisciplinary engineering skills at a level considered to be a specialist amongst generalists to manage interfaces and complex integration between teams of domain specialists.[5] Acquiring such knowledge will require meaningful multidisciplinary exposure and a commitment to remain in the field for a long time. As a guideline, the SE "T" model for career progression suggests that more than 20 years of appropriate experience is required to acquire the breadth of domain knowledge necessary to progress into program lead or project engineering manager roles.[6]

System engineering managers (SEMs) must develop such capabilities since the success of a project, from a SE management (SEMgmt) perspective, is not measured based on quality, cost, and schedule in the short term but also on plant performance over its total operational life.[7] Failure to develop these skills leads to cost escalation, schedule overruns, and performance implications. In many instances, performance issues do not show immediately, but as operational costs escalate over time.

This has been a constant challenge for South African organizations, with many megaproject failures impacting the economy in recent years. Prime examples are the Medupi and Kusile plants at Eskom.[8] Some general causes of poor performance were late approval of contracts and design drawings, design errors, poor scope definition resulting in late scope changes, and poor technical management capabilities.[9] A significant component of the project's failings can be attributed to poor SEMgmt capabilities during the project lifecycle. An engineering manager from a functional background or operations support role does not possess the appropriate experience or skillset to perform the role as a technical track lead of large complex SoSE projects. That is the function of an SEM who is considered an expert in managing complex interfaces and integration. Where do these individuals come from, given that they are so challenging to develop?

This research aimed to identify gaps in the development of SEMs and apply these findings to propose a framework to support the improvement of SEMgmt capabilities within the sector through internal development of resources or direct recruitment. A model to support the application of the framework was also developed. This paper includes the outcome of the literature review, the conceptual model and the methodology used. Research findings are presented under results, a new development framework, and a model in the discussion section, followed by a conclusion with recommendations.

2 | LITERATURE REVIEW

The literature review used draft research questions that informed phrases and keyword searches as subsection headings. Search questions were designed to explore literature from a broad range of fields, such as SE, ST, engineering management, project management, and construction management, to identify relationships with poor performance in SEMgmt. An overview of research with analysis applicable to the search questions is provided. The entire process is depicted in the mind map in Figure 1.

2.1 | What is the influence of systems thinking on systems engineering?

ST is a major high-order thinking capability that allows individuals to view systems as a whole, enhancing success in performing SE tasks.[10] Educators and practitioners have acknowledged the value of ST and its positive influence on successfully designing large-scale complex systems. It plays a vital role in mitigating several problems resulting from the increasing complexity of large-scale engineered systems.[11] The ST paradigm, which supports a holistic approach to evaluating solutions to complex problems, will prevent teams from solving the wrong problems precisely. Holistic systems thinkers must resolve complex multidisciplinary problems requiring collaboration.[7,12] There is no one-shoe-size-fits-all approach to ST. Systems engineers must possess skills and experience to apply a "systems view" or display a high ST capability to be successful in SE roles.[10,13]

Monat and Gannon[14] used examples of major project failures to highlight how the application of ST in early SE project development processes could have prevented adverse outcomes. Applying the outward-centric ST in SE enhances the ability to identify external

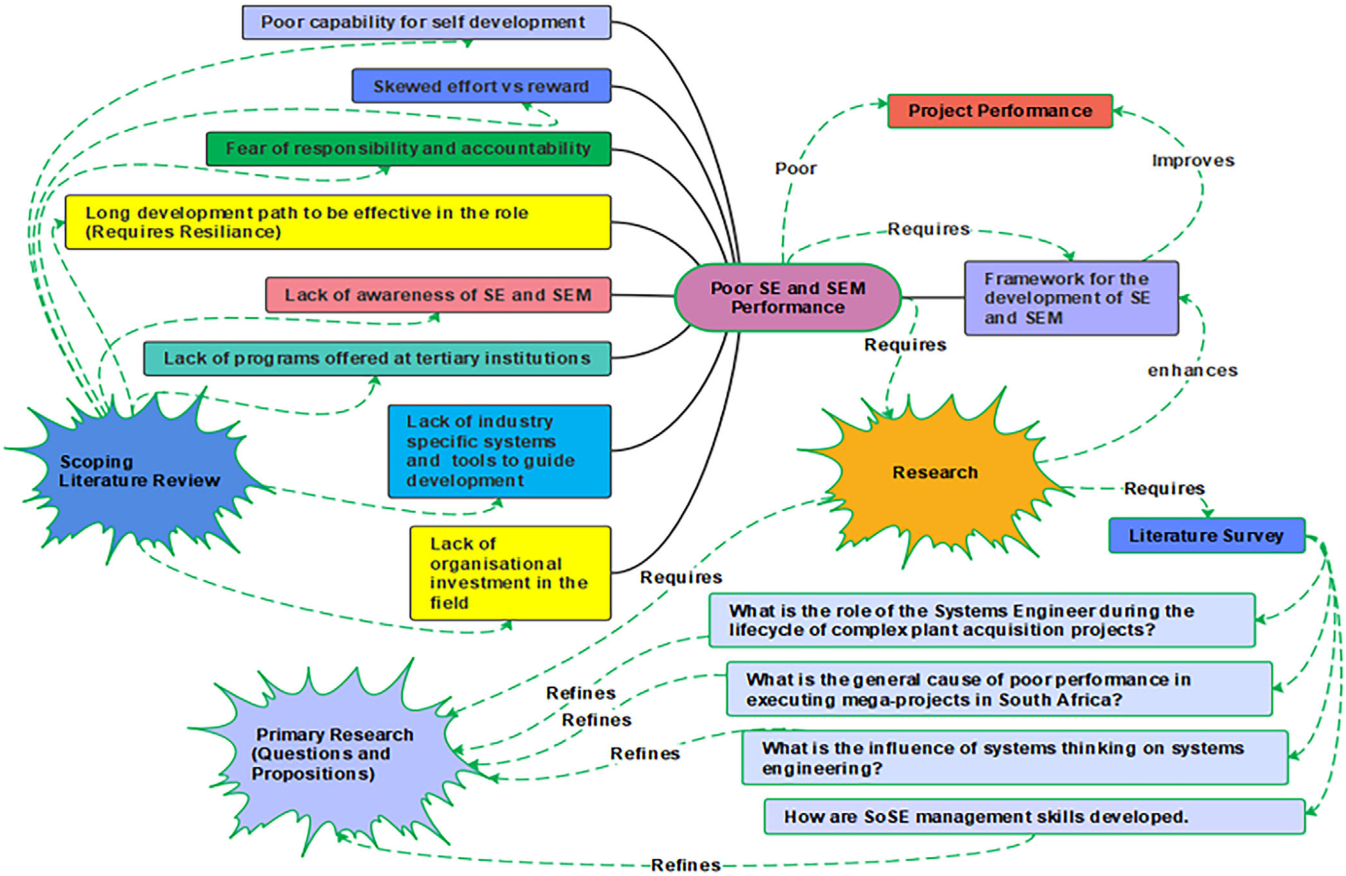

FIGURE 1 Mind map of research method.

factors such as environmental factors (temperature, wind, rain, sources of resonance), social factors, esthetics, maintenance, and disposal to ensure that the developed system is both technically and commercially successful.[14] The broad-based ST approach identifies and interprets relationships between components, their global impact on the system, and how they interact with the external environment.[15]

Monat and Gannon[14] argued that although there is an awareness of the synergistic relationship between ST principals and SE, limited literature is available to guide how to apply ST to SE. ST in engineering had been understudied due to a limited group of authors contributing to publications in engineering.[11]

Gaps—Several scholars have raised gaps regarding the lack of research in ST associated with SE or frameworks on how to develop and apply ST within SE over the life cycle of process plant acquisition projects. Given that some scholars question whether ST can be developed combined with the absence of a framework applicable to this context, it is difficult to screen individuals with the potential to perform effectively in SE, which requires ST capability. Given that a few scholars have highlighted that ST capability improves a systems engineer's ability to apply the lifecycle approach of designing systems, one would assume that the skill is developed and improved in individuals through sufficient project lifecycle exposure on a range of complex projects.

2.2 | What is the role of the systems engineer during the lifecycle of process plant acquisition projects?

The systems engineer is the individual within the project team who (a) evaluates the solution to problems considering a broad range of relevant scenarios, (b) delivers a well-balanced technical solution, and (c) manages the integration between technical domain resources and specialists within design, safety, reliability, and constructability to develop the solution to complex SE projects.[16]

The dynamic nature of large complex construction projects comprises a variety of subsystems, such as design, procurement, contract management and administration, safety management, and risk management. Each subsystem performs a specific function, for example, the design team translates Users' requirements into design drawings and specifications for construction. These subsystems interface and interact with every other subsystem within the system. Changes in any subsystem generally directly affect others, causing the project to deviate with time. A typical example is a design change that affects the design subsystem but also affects construction, procurement, and risk management subsystems. Changes in procurement may impact construction. Procurement may need to supply alternative materials and equipment. New risks may materialize, such as schedule impact due to changes in material, equipment, or fabrication requirements. The final configuration of the project may differ significantly from its original concept, highlighting the dynamic nature of complex construction projects.[17]

Three competencies associated with knowledge and experience critical to a systems engineer's success include (1) an expert level of experience in an engineering discipline, for instance, process, electrical, or industrial engineering; (2) multidisciplinary and interdisciplinary technical knowledge of other engineering domains relevant to the work environment; (3) sufficient work experience as a domain engineer and systems engineer on several complex projects. SE experience in the industry is role-specific, for example, marketing versus integration lead in complex project development roles. The systems engineer's role depends on his level and experience within the project structure. The highest level of performance is the ability to analyze a situation, define the problem, develop a solution, and plan the implementation of the solution.[18] Such individuals will typically perform lead roles within the project structure.

Multidisciplinary knowledge does not imply a broad range of awareness or knowing a little about a lot. Although the level of multidisciplinary knowledge required by systems engineers need not be at a specialist level, a significantly high level of understanding is required to effectively manage interfaces and integration between specialists from supporting domains. Finally, based on their study, the authors proclaimed that the systems engineer's general field of specialization is electrical, electronic, or computer engineering.[19]

Gaps—Systems engineers and SEMs tend to be employed as technical track leads.[20] However, literature does not reference the generic engineering manager or engineering management role in SE project structures. Since process plant acquisition projects, such as a petrochemical plant, are defined as complex SoSE projects, it stands to reason that systems engineers and SEMs should perform the technical track leadership roles within project structures. Industries must start applying the correct terminology in the project delivery environment to avoid contaminating such structures with inadequate experience in project leadership roles.

Process plant acquisition projects are generally dominated by mechanical, civil, and structural hardware. A typical example of such a facility is a petrochemical plant, oil and gas facility or power plant. The technical team on such projects will generally consist of engineering representation from almost all engineering domains, for instance, environmental, geotechnical, civil and structural, process, controls and instrumentation, electrical, mechanical, metallurgical, and fabrication specialists. Systems in such facilities will typically consist of utility supply systems, feedstock, and raw materials handling systems, energy supply systems, control systems, production systems, and inventory management systems. Although control rooms, electrical substations and additional electrical and control artefacts can form a significant portion of the overall scope, it is generally dwarfed by mechanical, civil, and structural artefacts. An electrical or control engineer's background may not provide the broad exposure required to effectively perform the systems integration role in projects by applying the whole lifecycle approach accustomed to SE.

Zhu and Mostafavi[17] highlighted an example of a late design change that affects the design sub-system but also affects construction, procurement, and risk management subsystems. Such changes generally impact an array of interfaces, including metallurgy, the design team (modeling, mechanical and piping, process, controls and instrumentation, civil and structural), fabrication, procurement, construction management, risk management, and planning. Identifying the impact of change early is essential to effective change management, a critical skill in a complex, and large project environment. This further questions the electrical or electronic engineers' suitability to perform this role. A computer engineer does not apply to this context. Industrial engineers are commonly deployed in manufacturing industries, focussing on ensuring the efficiency of industrial processes. They may not be suitable to lead integrated project delivery teams as domain or systems engineers for plant acquisition projects.

The experience of process engineers in applying the whole life-cycle approach to design in this study is also questionable since many organizations limit process engineers to conceptual development exposure. On the other hand, the mechanical engineering degree is offered from a generalist perspective, covering electrical, electronics, fluids, thermodynamics, heat and mass transfer, metallurgy, vibrations (dynamics), mechatronics, hydraulics, the strength of materials as well as the design of physical artefacts as core elements.[21] Given that the mechanical and piping role on process plant acquisition projects overlaps the broadest range of domains, mechanical engineers are better suited to develop into and perform the role of the systems engineer and SEM effectively.

2.3 | How are systems engineering management competencies and traits developed to improve systems of systems engineering project success?

Given the criticality of the SE role, the screening process for shortlisting candidates should be stringent to ensure that only applicants who are likely to succeed are accepted. One of the key traits to enhance success in SE positions is a keen interest and strong will to be a systems engineer.[22] Placing the wrong candidates in SE positions can be an expensive error, given the cost of development and errors on SE projects.[18]

Gaps—Since domain-specific skills are critical to systems engineers' performing roles in process plant acquisition projects, industries lacking screening tools or frameworks are often guilty of applying poor selection processes for SE roles. Scholars, communities, and organizations develop frameworks from a general or specific industry perspective. None of the literature or existing frameworks provides guidelines on how these skills can be developed or applied as part of a competency development program. An example is the INCOSE framework, which prescribes skills and competencies applicable to SE.[23] Although INCOSE does well to isolate the core competencies applicable to SE, it does not provide a criticality ranking for these skills, which might benefit large industries undertaking large-scale acquisition projects. A criticality ranking will guide the development or acquisition of a systems engineer from a risk perspective, ensuring that development and acquisition are based on skills deemed essential for effective performance in the role. Since SE and SEMgmt competencies are context-dependent, and extant literature suggests that a systems engineer and SEM should be an expert in a field and have an overarching knowledge of all other domain engineering fields applicable to his application context, INCOSE's prescribed list of core skills may be inadequate. The latest INCOSE framework excludes domain-specific skills since this is industry-specific, which introduces other challenges. Since domain-specific skills are critical to systems engineers performing roles in process plant acquisition projects, industries lacking screening tools or frameworks are often guilty of applying poor selection processes for SE roles.[23]

2.4 | What is the general cause of poor performance in executing megaprojects in South Africa?

Surveys with quantity surveyors, engineers, and project managers who participated in South African megaprojects (Medupi and Kusile) revealed that poor planning, slow decision-making, inaccurate estimation, increased material costs, and late contract awards were the primary causes of cost and schedule overruns. Poor management resulted in design changes, late approval of design drawings, design errors, and late scope change (on-site) during these design and construction projects.[9] Planning, decision management, procurement and contract management, risk management, concurrent engineering, design integration, and interface management are all roles and responsibilities of systems engineers and SEMs.[24] These failings indicate poor SE and SEMgmt performance on these projects.

Applying a one-size-fits-all approach to the execution of projects in Africa is another underlying cause of poor performance. Although there were several issues with the Medupi project, items captured under management and organizational problems were poor consideration of water availability (water scarcity), health implications for nearby communities and challenges with local services and capabilities within the project design phase.[25] This indicates a failure to apply the ST paradigm, which supports a holistic approach to evaluating solutions to complex problems during the project's design phase.[12]

Medupi, Eskom's most significant single investment in 60 years, intended to supply 10% of SA's electricity demand, generates more emissions than 63 of the lowest-emitting countries combined.[26] Based on increasing coal costs and emission constraints, Kusile and Medupi will operate at reduced load factors from 2026.[8] This indicates failures to apply the holistic approach of ST and the life cycle design approach from SE. This also highlights failings in multidisciplinary and cross-functional interface management, which is a responsibility of the SEM. ST, SE, and SEMgmt capabilities appear to be gaps in project delivery structures in the sector.

3 | RESEARCH METHODOLOGY

3.1 | Ontology and epistemology

The nature of the research problem, questions, and propositions were aligned with a relativist ontology and a constructionist epistemology, that is, many truths apply to this topic or questions.[27] However, not all were relevant to the context of this study. For instance, no single reality or issue impacts the development of systems engineers and SEMs in South Africa. Examples are socio-economic conditions within the country, resulting in limited resources to fund projects to support development and encourage staff retention, and corruption which also constrains resource availability. Such issues are not directly within the control of tertiary institutions or industries and have little relevance to a framework for developing system engineers and SEMs. Furthermore, the viewpoints of the individuals regarding barriers to performance will vary based on their perspectives and experience.

3.2 | Outcome of secondary research (literature review)

The literature review combined a structured narrative method with a critical review. Open-ended search questions based on research questions were designed to allow a rich data pool to be gathered. The primary focus of the research was highlighting gaps in the development and capabilities of SEMs in process plant acquisition projects in South Africa. Peer-reviewed journal articles were preferred. The number of citations was also used to measure the quality of the source data. Old, outdated material was generally discarded.

The literature review highlighted the need for a development framework to improve SE and SEMgmt in South Africa. Findings from the literature review were also used to develop the preliminary competency framework based on the INCOSE framework for the industry context. Domain engineering skills, which included metallurgical, welding, mechanical, civil, structural, control, electrical, process, environmental and geotechnical engineering competencies, were added as an additional column to the proposed framework. Although the framework was developed for SE, it is also relevant to the field of SEMgmt, which is the most advanced role in the SE career ladder. The approach was to identify critical competencies that can be considered a risk, that is, competencies that cannot be generically developed. These critical competencies should be used to screen applicants who are most likely to be successful in the SE field applicable to the industry context. This ensures a strong pool of candidates with the capabilities to develop the characteristics required to progress into SEMgmt roles successfully. The second area of interest was the critical competencies required to be successful as an SEM in this sector.

3.3 | Primary research design

The primary research design was aligned with a qualitative research paradigm to develop theories and foundations to validate or reject the research propositions proposed based on secondary research.[28]

Research questions were designed to validate the need for a framework, establish the most effective way to apply the framework as a resource development or resource acquisition tool within the sector and determine the critical competencies required to be successful in the SE field. Research propositions derived from the literature review and aligned with the research questions and content of the proposed framework are outlined below:

- **Effective screening for SE roles**—SE roles in complex SoS construction projects are among the most demanding in the SE field. Progression to the roles of senior systems engineer and SEM requires high intelligence, resilience, and strength of character to shoulder the overall responsibility and accountability that comes with such positions. Not everyone can be effective in this role; for instance, domain engineers from large projects and maintenance may not be interchangeable. SE errors in the construction industry represent not only a significant cost risk in the short term but a long-term risk due to poor plant performance or being beaten to the market by competitors because of schedule delays. This leads to the following research proposition:

  P1: Stringent competency screening tools for SE roles will assist in improving SE and SEMgmt performance.
- **The long road to success**—Gaining skills to perform at higher levels within the project hierarchy requires patience and a desire to remain in the field for a long time. This is because of the broad range of competencies required to be effective in these roles. It also requires exposure to suitable environments to develop the range of knowledge required to be effective at interface management and integration. Although a career in SE may not be ideal for those pursuing instant gratification, organizations need to be wary of talent and implement effective reward strategies to retain system engineers. Systems engineers are specialists with context-specific skills requiring a long turnaround time to replace lost capability. In some instances, lost capability cannot be replaced. This leads to the following propositions:

  P2: Individual capability and prior experience impact knowledge adoption rate and performance in SEMgmt roles.

  P3: Context-specific experience is directly linked to effective performance in SEMgmt roles.

  P4: Interdisciplinary, multidisciplinary, and cross-functional knowledge is directly linked to effective performance in SEMgmt roles.
- **Core skills of systems engineers for process plant acquisition projects**—Some skills are more important than others in SE roles, considering that few individuals can acquire all the competencies before performing the role or within his/her career. An example would be interpersonal skills or people skills. An individual scoring high on people skills and low on technical skills will not necessarily be capable of developing the technical skills. This leads to the final proposition:

  P5: Some skills are more important than others to perform successfully in SEMgmt roles.

3.4 | Primary data gathering and analysis

Primary data were gathered using one-on-one structured interviews as opposed to focused groups. This helped manage bias and ensured that the collected data represented the respondents' views. Open-ended interview questions were designed to test the relevance of the research questions and propositions.

Interview candidates were selected to achieve diversity in age groups, experience, various roles (systems engineers and SEMs), users (client organizations), and consultants. Users considered were organizations in the petrochemical, energy, and mining sectors, and consultants were employees from subsidiaries of international consultancies based in South Africa. Some had experience in the aerospace and defense industry to compare data from the process industry to an industry where SE was already established as a field. The sample consisted of 19 participants with an average experience of 25 years in the field. Gathering data from diverse sources allowed the problem to be evaluated from different perspectives to improve data triangulation.

Data were analyzed using ATLAS.ti software with a combination of deductive and inductive coding methods to achieve data triangulation. Themes were the common topics under which groups of interrelated codes were consolidated and discussed. Criteria used for the selection and discussion of results (codes) under relevant themes were (a) the number of individuals who cited codes related to the research context, (b) the frequency that a code was cited in transcripts in a variety of contexts relevant to a research question or proposition and (c) the importance of codes or responses to the research topic and questions/propositions. A few extracts from transcripts are presented in this paper to strengthen arguments and validate results. Transcript codes were provided with quotations for traceability.

The relevance of the research propositions was validated based on the data analysis outcomes from primary research (interviews), that is, the primary research was used to validate the outcomes of secondary research. Research propositions that positively impacted SE/SEMgmt and project performance validated the relevance of the content of the proposed competency development framework. The research propositions originally proposed were not exhaustive, that is, research propositions were modified based on new findings that emerged from inductive research methods. The final SE/SEMgmt competency development framework proposed in this paper is the outcome of an iterative process.

4 | RESULTS AND ANALYSIS

4.1 | Awareness of the systems engineering field, availability of systems, and tools

From a sample of 19 interviewed individuals, 17 respondents demonstrated an appreciation of SE aligned with definitions developed within the SE field and applicable to SE/SEMgmt in the project execution context. In South Africa, SE is recognized and defined in the aerospace and defense industry. Organizations within this sector have traditionally supported growth within the function by developing courses to enhance the competency of SEMs. Interviewees from the aerospace and defense sector demonstrated a stronger appreciation of the field and familiarity with its terminology, role requirements, development opportunities, systems and tools, including bodies of knowledge available to guide the development and improve performance in SE. All aerospace and defense industry candidates are active members of INCOSE.

Respondent T016—*"I am one of the contributors to the INCOSE competency framework. So, I'm familiar with the descriptions."*

Although most candidates from the petrochemical sector demonstrated a strong appreciation of SEMgmt, this was primarily gained through experiential growth and self-development over time, as opposed to organizational awareness, systems, and tools available to guide candidates through the development process. Respondents from this sector were less familiar with terminology from the SE field. Candidates were not active members of INCOSE and lacked awareness of systems, tools, and bodies of knowledge available to support development, contrasting with their counterparts from the aerospace and defense sectors.

Respondent T005—"In terms of the experience and performance in the role, I don't think this was clearly defined upfront in terms of what is the requirement, and what are the competencies required. It was basically up to the individuals to make this work or not."

Respondent T001—*"The responsibilities of system engineers. I don't have contexts for systems engineers. I need to just ask that clarification."*

Organizations and individuals within the energy sector demonstrated a lack of familiarity with the roles and responsibilities of systems engineers and SEMs within the project delivery environment.

Respondent T015—*"So system engineering managers, they do not get involved in the technical interfaces."*

Findings indicated a general lack of awareness of the SE and SEMgmt field amongst individuals and organizations within process industries. This often contributed to a poor or no definition of requirements for SE roles and a lack of systems, tools, and processes to support individual development. A consequence is poor SE and SEMgmt capabilities within project delivery, poor deployment of resources, and poor project performance at individual and organizational levels. Additionally, some individuals within the sector interpreted SE to imply maintenance of engineered systems (maintenance management). These findings are aligned with the literature review, which indicates that SE only started to grow as a field in engineering in the 1990s.[2] The field is still in its infancy and has yet to be adopted by organizations in the process industry, within project delivery. A development framework for this sector will not only provide a guideline to individuals looking to identify development needs but will also support resource acquisition by indicating competencies and traits of individuals most likely to succeed in SE and SEMgmt roles. This validates research proposition P1:

P1—Stringent competency screening tools for SE roles will improve SE and SEMgmt performance.

4.2 | Poor deployment and development practices

Some important issues highlighted by respondents within the petrochemical and energy sector regarding SE and SEMgmt capabilities or performance within organizations included a lack of support and knowledge transfer through coaching and mentoring and a lack of functional support and tools to guide development and performance in the role. Many respondents within the sector attested to having a poor understanding of the role requirements upon appointment into the position. Organizations rely on experiential learning (self-development) with little or no guidance.

Respondent T004—"There was a function called engineering management in the past.… Unfortunately, when I came into the space, the function was drastically scaled down and development plans were not in existence …. A lack of development significantly effects how we perform in this role.… Considering what I had to learn as part of on-the-job training, some of those learnings came at the expense of errors."

Rigid matrix structures within large organizations hinder the development of broad-based engineering knowledge and project lifecycle experience. Respondents within large organizations highlighted challenges associated with acquiring multidisciplinary engineering exposure. Training within functions is limited to developing and performing domain engineering skills. However, it is not adequately geared to allow the appropriate development of broad-based engineering skills due to limited exposure to interface and integration management across disciplines and project functions. This contrasts with smaller organizations that are more flexible with resource movement and role interchangeability.

Respondent T001—*"What would have made me more comfortable in that role (SEM) is to have a brief overview of what the other disciplines do."*

Some respondents from the process and mining industry highlighted that individuals from mechanical and process engineering backgrounds held a distinct advantage in progressing into the SEM roles due to the greater number of interfaces between the two functions in process plant development projects. A few highlighted the view that the broad-based structure of the mechanical degree presented an advantage to those of mechanical origin, in understanding the interfaces and integration between disciplines necessary to lead large complex projects.

Respondent T012—"Better engineering managers are always mechanically trained. In the South African context, mechanical engineers are exposed at the university level to structural design, mechanics of materials, strengths … as well as electrical and control systems."

In general, findings highlighted a lack of structured development as a major barrier to the effective transition from domain engineering to SEMgmt roles. The issue is greater within the process industry, where the SE field is yet to be adopted in project delivery. The biggest obstacle was a lack of exposure to multidisciplinary project interfaces and requirements in domain engineering roles as part of career progression. Some participants highlighted that mechanical and process engineers held a distinct advantage in acquiring this knowledge within integrated project teams. Given that the SEM performs the technical track leadership role on complex SE projects[24] and that systems engineers and SEMs are part of the same career ladder,[29] the basic understanding of multidisciplinary and cross-functional integration requirements should be acquired as a systems engineer (domain engineer), prior to progression into the SEM role.[24,29] This was also highlighted by Frank and Kasser,[18] who indicated that multidisciplinary and interdisciplinary technical knowledge of other engineering domains relevant to the work environment was critical to a systems engineer's success.[18] The progression of domain engineers into project engineering manager or SEM roles, with significant gaps in their understanding and exposure to interface and integration requirements necessary for delivering the integrated solution, exposes weakness in developing project lead engineers within large project organizations in South Africa. Findings supported literature which indicated that the general causes of poor performance in large infrastructure projects are late approval of contracts and design drawings, design changes, design errors, poor scope definition resulting in late scope changes, as well as poor technical management capabilities.[9] These findings are aligned with research proposition P3:

P3: Context-specific experience is directly linked to effective performance in SEMgmt roles.

4.3 | Experiential requirements and critical competencies for systems engineering management roles

Critical competencies and traits viewed as necessary for development and performance in SEMgmt roles were based on the number of respondents who highlighted its importance during interviews and the number of times it was cited in relevant contexts. Results were grouped under three themes: broad-based engineering knowledge, general competencies, and personality traits.

Figure 2 indicates that broad-based engineering knowledge is critical to success in SE roles. ST was considered a critical competency by 95% of the respondents, followed by interdisciplinary and multidisciplinary domain knowledge mentioned by 89%, cross-functional interface and integration management highlighted by 74% and finally, understanding multidisciplinary risks and project lifecycle experience mentioned by 53% of the pool.

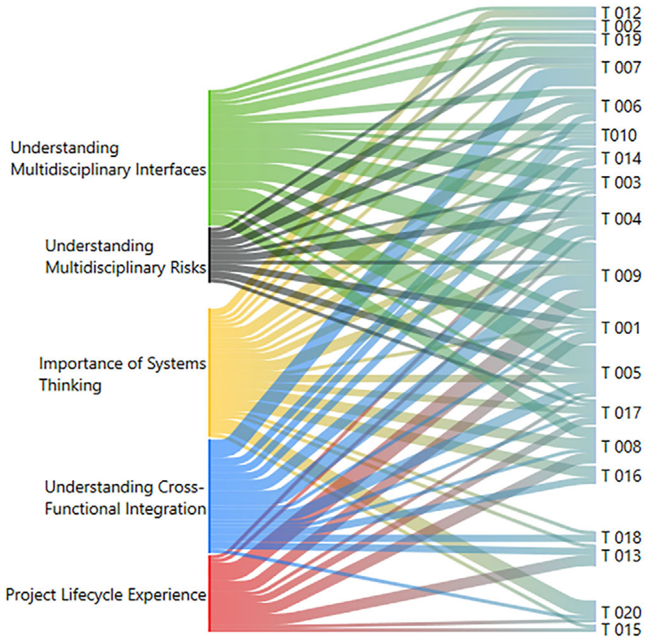

FIGURE 2 Broad-based knowledge essential for success.

Besides broad-based engineering knowledge, additional competencies deemed essential for career progression in SEMgmt roles were grouped under general competencies, illustrated in Figure 3, and include project framing, requirements engineering, context-specific experience (large project exposure), contracting and contract management. Project framing was highlighted as a critical competency by 68% of the interview sample, followed by requirements engineering by 63%, context-specific experience by 42% and contracting and contracts management by 32%.

Figure 4 illustrates respondents' views on personality traits necessary for success in SEMgmt roles. Sixty-eight percent of the respondents indicated that the role is unsuitable for discipline specialists such as static equipment specialists, hydraulic specialists, and heat transfer specialists who prefer to focus on detailed design and analysis aspects. Forty-seven percent indicated that leadership traits were important. This was followed by people management at 32%, the need for an assertive character at 26% and the need to be performance-driven at 21%.

Findings indicated that a broad range of knowledge and experience, which included multidisciplinary, cross-functional exposure, risk management, project lifecycle experience, and ST, are essential elements for effective performance in SEMgmt roles. Lifecycle experience and ST play an essential role in project framing, requirements definition, and scope development since they allow the project engineering manager/SEM to plan the technical strategy based on a futuristic snapshot of project development. It also allows the SEM to apply this experience to optimize solutions that balance capital and operational expenditure, that is, develop solutions optimized for short- and long-term cost benefit. Other competencies that were viewed as critical to enable success included the need for context-specific experience,

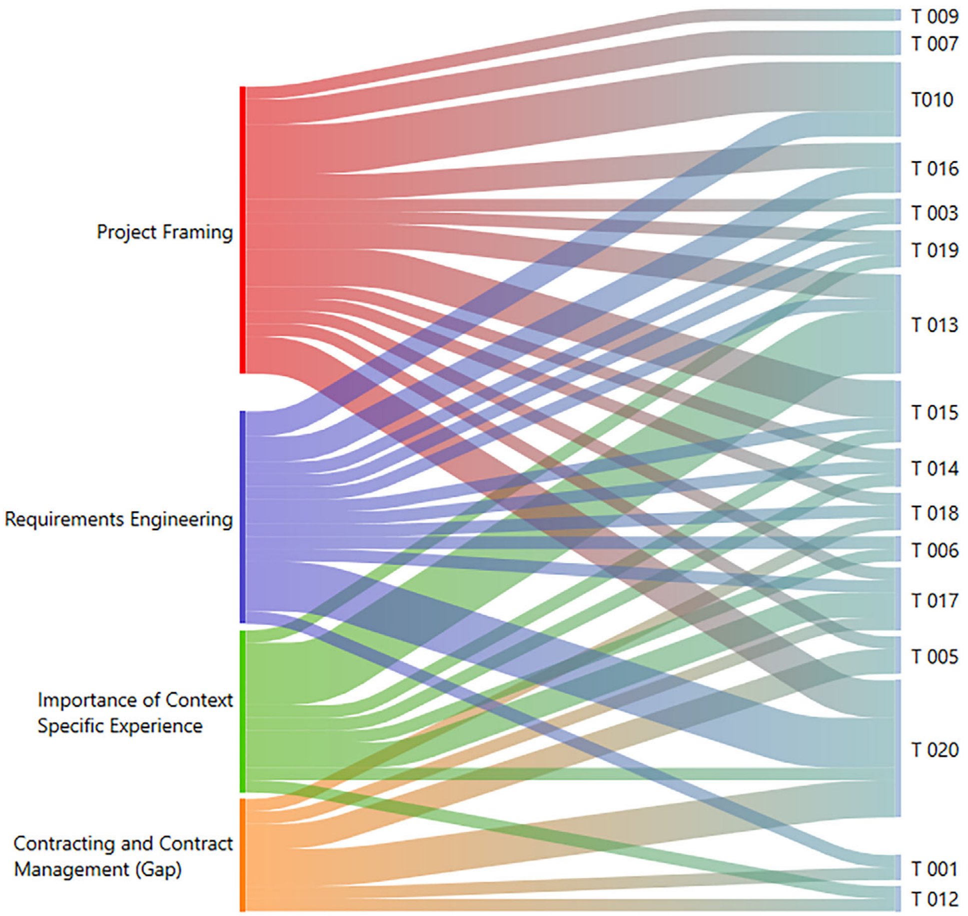

FIGURE 3 General competencies.

project framing, requirements engineering, as well as knowledge of contracting and contracts management.

These skills are essential since the success of an SEM is not measured based on quality, cost, and schedule in the short term but also on plant performance over its operational life (typically decades).[7] Recent highly publicized failures of Medupi and Kusile highlighted shortfalls in technical leadership capabilities within large, complex projects. Both Kusile and Medupi will be operated at reduced load factors from 2026, based on a combination of increasing coal costs and emission constraints.[8] This indicates a failure to apply the ST paradigm and lifecycle approach to engineering design.

Some personality traits deemed critical for the role included leadership, people management skills, an assertive character, and a natural inclination to drive self-development and performance. Interestingly, qualitative feedback revealed that broad-based engineering skills (technical skills) were ranked higher than personality traits (soft skills) as an enabler to success in SEMgmt roles. This aligns with extant literature, where scholars suggest that soft skills are the least significant for screening suitability for effective performance in SE roles.[30] Findings also emphasized the specialized nature of the role, its lack of suitability to domain engineering specialists and the need for specific character traits to be successful as an SEM. These findings support literature findings and research propositions P2–P5:

P2: Individual capability and prior experience impact knowledge adoption rate and performance in SEMgmt roles.

P3: Context-specific experience is directly linked to effective performance in SEMgmt roles.

P4: Interdisciplinary, multidisciplinary, and cross-functional knowledge is directly linked to effective performance in SEMgmt roles.

P5: Some skills are more important than others to perform successfully in SEMgmt roles.

4.4 | A Competency development framework and its application within the sector

Respondents were asked to share their insights on how to apply the framework as a development tool within the process industry. Most found it challenging to outline competency development as a chronological or sequential process given the structure of large project organizations within the sector and the integrated project environment in which development occurs. A valuable insight was that SE and SEMgmt competency development should be viewed as a three-dimensional process within large project environments. Although all engineers start developing within their domain or engineering designation of origin

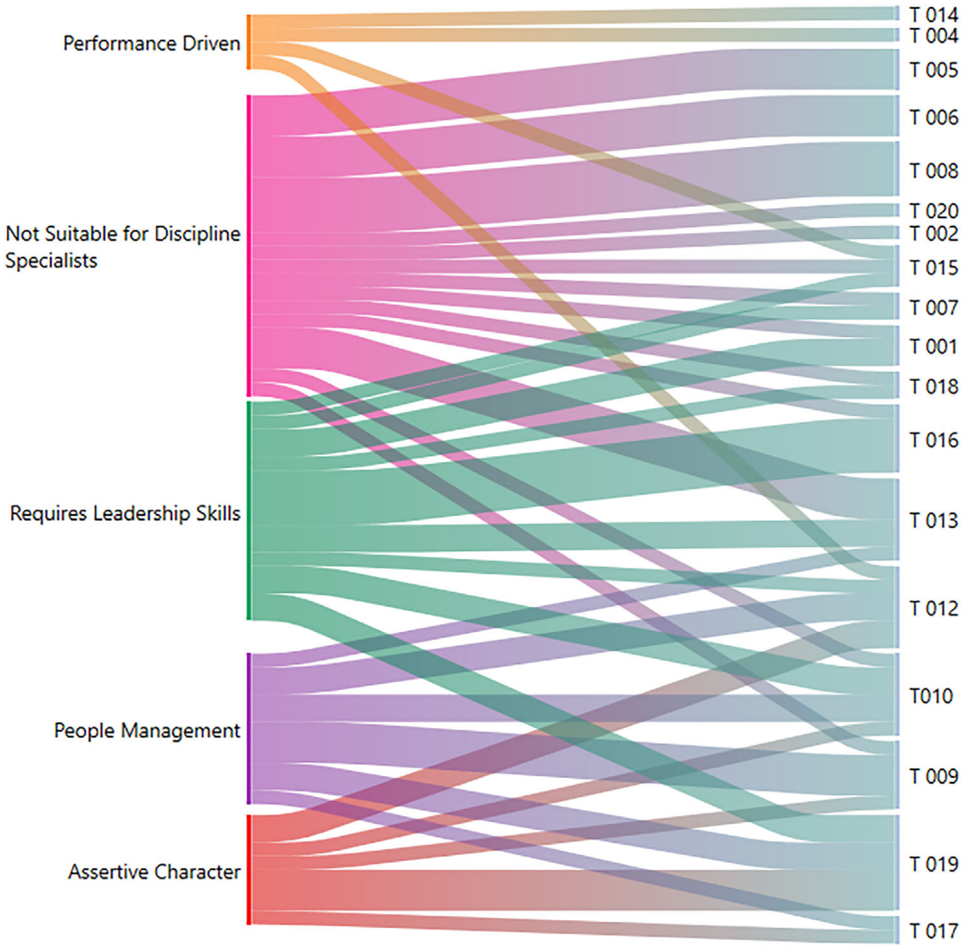

FIGURE 4 Personality traits.

as part of a graduate development program, a significant component of their competency development occurs in parallel through exposure and experiential learning within integrated project teams in large projects. This exposes domain engineers or project lead engineers to interface management and integration at the SE level; however, the extent of the exposure is dependent on the number of interfaces applicable to the domain, based on project definition or complexity, that is, some domains, for example, mechanical and process designations gain greater exposure than others.

Respondent T007—"So, maybe my view is a little bit more 3D as I start from my specific discipline. But as I am learning my specific discipline, I'm starting to learn some aspects of all these other columns as well. Maybe just on a very small scope."

Findings indicated that domain engineers are passively exposed to interfaces and integration management, verification and validation, project lifecycle exposure, planning, concurrent engineering, and the like through active participation and experiential growth within an integrated project environment. In this environment, ST skills are developed and improved with experience, growing stronger amongst individuals with a natural inclination for big-picture thinking. Experienced individuals highlighted that developing professional and management competencies is an ongoing process that matures in individuals as their capabilities improve. A fascinating insight was that the development of professional competencies starts when one's career starts and ends when an individual retires.

Most interviewees highlighted the importance of developing a solid foundation of domain engineering competencies, including multidisciplinary engineering exposure and system engineering technical and core competencies, before shifting focus to developing management and integration competencies. Similar sentiments were shared regarding applying the framework as a recruitment tool. Experienced professionals highlighted the importance of screening candidates for demonstrated experience in elements that form the foundation of the SE field when considering appointments within higher levels of the SE hierarchy. The general view was that professional competencies, although important, are considered equally important and applicable to many other fields and functions. SE competencies to perform at higher levels within the systems hierarchy, such as SEM roles, are scarce skills that are difficult to acquire. The broad range of competencies required is often beyond the capabilities of the average engineer. Managing higher level appointments with a high emphasis on professional and management competencies but major gaps in technical competencies was raised as a high risk to project performance. Individuals may not necessarily possess the natural propensity or

TABLE 1 Competency development framework.

SE core competencies	Professional competencies	Technical management competencies	SE technical competencies	Project integrating competencies	Domain engineering competencies
Systems thinking	Ethics and professionalism	Planning	**Requirements definition**	Project management	**Mechanical engineering**
Lifecycles	**Technical leadership**	Monitoring and control	System architecting	Finance	**Civil engineering**
Capacity engineering	Negotiation	Decision management	Design for:	Logistics	**Structural engineering**
Critical thinking	Team dynamics	Concurrent engineering	**Integration**	Quality	**Control engineering**
Systems modeling and analysis	Communication	Business and enterprise integration	**Interfaces**		**Electrical engineering**
Contracting and contract management	Emotional intelligence	Acquisition and supply	Verification		**Process engineering**
	Coaching and mentoring	Information management	Validation		**Environmental engineering**
	Facilitation	Configuration management	Transition		**Geotechnical engineering**
		Risk and opportunity management	Operation and support		**Metallurgy and welding**

capability to address those gaps. Furthermore, the fast-paced and high-pressure environment within complex large projects is not suitable for addressing such gaps.

Findings regarding experiential requirements, critical competencies and traits, and insights on how to apply the framework were consolidated to develop an industry-specific competency development framework illustrated in Table 1. General engineering, which was proposed in the INCOSE template, was removed since these aspects are covered under domain engineering development. Contracting and contract management, which were considered critical competencies in this research, were included as core SE competencies. Critical competencies highlighted in bold font must be comprehensively screened when recruiting for higher-level roles within the SE hierarchy.

Consolidated findings from the qualitative feedback regarding the importance of the approach and the most practical way to apply the competency development framework within large project organizations in the sector were used to develop a practical model presented in Figure 5. It indicates that development starts as a domain engineer focusing on developing solid interdisciplinary and multidisciplinary domain engineering skills applicable to the project organization.

Through exposure to integrated projects of varying sizes and complexity, SE technical and core competencies are developed concurrently as part of experiential growth as a domain engineer. As one progresses to higher levels within the hierarchy, as a domain engineer, one should consider external courses and management programs to cement one's theoretical grounding in the SE field. Findings indicated that domain engineering and SE technical and core competencies were deemed essential, forming the foundation to progress into SEMgmt. Management and integration competencies associated with project management become essential as one progresses to higher levels

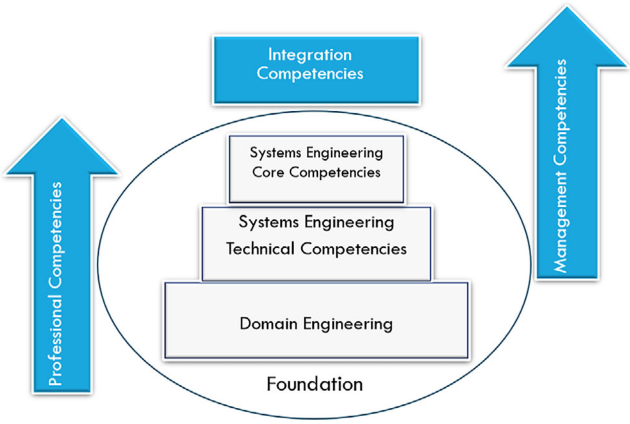

FIGURE 5 Model for the application of the development framework.

within the SE hierarchy. Professional competencies are required at all levels in SE roles but mature in individuals as experience and capability improve.

The "T" model for systems engineer career development illustrates that the higher the role within the SE career hierarchy, the greater the breadth of domain knowledge required to perform successfully. A general guideline was 9–12 years of appropriate experience to perform as a systems engineer and 13–20 years of experience to perform the role of large project lead.[6] Based on this, one would recommend pursuing engineering management-related degrees in preparation for large project lead roles, approximately 9–12 years into continuous career development as a systems engineer on large projects. This ensures that individuals invest in further development within a career where they have demonstrated the propensity to succeed.

5 DISCUSSION

The study indicated that a framework for developing SEMgmt within the process industry would assist in improving SE and SEMgmt performance within the sector. These findings aligned with the literature survey results indicated that an improvement in SEMgmt will improve interdisciplinary, multidisciplinary, and cross-functional interface integration in projects. This, together with the application of project lifecycle considerations and ST, improves the quality of requirements engineering, ensuring that aspects such as geographic and environmental requirements, legislation, codes and standards, owners' specifications, operations, maintenance requirements, construction requirements, and gaps or project-specific requirements are accurately defined. This results in higher quality scopes, reducing scope change. Concurrently, this improves risk management capabilities, quality of project management support (project framing, planning, execution and quality assurance/control), and ensures effective contracting strategies and information management.

Effective contract management and information transfer during design development improves the quality of concurrent engineering, that is, the interfaces and information flow between teams responsible for developing independently procured systems and the integrated design package. Typical systems include mechanical, electrical, and electronic equipment and appurtenances. Information delays or late changes within these systems, such as technology changes, have a knock-on effect on the integrated systems, impacting equipment layout, support requirements, system configurations, and interface loads. A change in technology requiring a configuration change will often have a knock-on effect on other technologies due to changes in hydraulic and pneumatic requirements that impact the sizing of pumps, compressors, and blowers within the system. This may impact energy demand due to changes in motor sizing. This domino effect impacts various elements of discipline engineering (interdisciplinary), other disciplines (multidisciplinary) and functions such as cost control, planning, and contract management, to name a few. Ultimately, an improvement in requirements engineering and framing resulting in higher quality scope definition combined with improved planning and risk management improves procurement management and information transfer, improving design quality and schedule.

This reduces changes associated with the fabrication of independent systems and integration of the independent systems into the SoS during construction. Typical fabrication and construction changes include equipment modifications and site clashes resulting in changes in configuration and requalification of quality assurance and quality control procedures. A consequence of effective interface integration during project development resulting from an improvement of SEMgmt is an improvement in the overall project performance (cost, schedule, and quality). This improves organizational performance in the short term through direct project costs and in the long term through a higher performance of the facilities (higher reliability, lower maintenance, and operational costs), improving cash flow and thus reducing the payback period. The organization will have financial resources to attract and retain a strong talent pool, provide resources, and fund a regular pool of projects to support continuous development and sustain a high level of SE performance.

6 CONCLUSION AND RECOMMENDATIONS

This research was undertaken to investigate the general causes of poor project performance within the process industry, which included organizations in the mining, energy, and petrochemical sectors. The aim was to determine the need for a competency development framework for the sector, establish its contents and present a model for its application to guide resource development and acquisition within the sector.

The results highlighted several contributing factors, such as a lack of industry and individual awareness of SE as a field, rigid structures within large organizations, which limit access to knowledge transfer, and a lack of mentoring, coaching, systems, and tools to guide the development of systems engineers and SEMs within the sector. Further findings indicated that poor deployment of resources within higher levels of the SE hierarchy also contributed to poor project performance. Once again, this was primarily due to a lack of awareness of experiential requirements and critical skills and traits required to perform successfully in SEMgmt roles.

Some insights from industry specialists regarding experiential requirements, critical competencies, and traits required for successful performance in SEMgmt roles included the importance of multidisciplinary domain knowledge, cross-functional knowledge, lifecycle experience, and an inclination for ST and technical leadership traits. Results were consolidated to develop an industry-specific framework, which is presented in Table 1, to guide resource development and support recruitment processes within the field. A model to support the application of the framework is presented in Figure 5. This will assist in improving SE and SEM development and performance.

Some limitations of this research included time constraints since the study was conducted as part of a mini dissertation limited to an academic year and limited access to published data regarding organizational project performance. A general observation from this study was that individuals performing the technical integration lead roles within the WBS of large projects in the process industry are referred to as engineering managers and not SEMs, although they are expected to perform the functionality of an SEM. A consequence is a skewed understanding of the role requirements and a lack of awareness of systems and tools already available in the SE field. It may be worth investigating why the official adoption rate of SE as a field is so slow in the project delivery environment within this sector, given that it started to grow within other industrial sectors in the 1990s.[2]

Finally, lack of knowledge transfer due to a lack of mentoring, coaching, and rigid organizational structures was raised as a barrier to effective performance in SE roles. Students could explore appropriate organizational structures within organizations in the process industry to enhance knowledge transfer, SE adoption, and capability.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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