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MBSE-LITE: A FRAMEWORK FOR ADOPTING MODEL-BASED SYSTEMS ENGINEERING IN SMALL AND MEDIUM-SIZED ENTERPRISES IN SOUTH AFRICA

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Abstract. *Purpose* – This research aims to characterise the landscape and factors for successfully implementing Systems Engineering (SE) and Model-Based Systems Engineering (MBSE) in the enterprise.

Research methodology – The study investigated the factors across different industries that affect the success of MBSE in an enterprise using a survey questionnaire. The research focussed on the uptake and implementation of MBSE in Small and Medium-sized enterprises (SMEs) in South Africa. More than 100 industry professionals participated in the study.

Findings – The survey revealed that SMEs have trouble adopting and implementing MBSE because they are unaware of its applicability and lack economic justification and support from upper management. Quantitative data analysis assessed how factors such as MBSE training, existing SE processes in the enterprise, and how long the company has been using MBSE contribute to the success of MBSE adoption in SMEs.

Research limitations – The population size limited the study reached and the time available to conduct the research. However, it does not reduce the results' strength and validity.

Practical implications – The analysis showed that training and an existing SE structure are highly significant, while the age of MBSE in the enterprise does not correlate with its success. Therefore, these results proposed an adoption framework for SMEs in South Africa to aid MBSE adoption by incorporating training and a clear uptake and implementation process.

Originality/Value – This research builds on the growing body of literature about implementing MBSE and enterprises. The conclusions provide valuable insights and guidelines for implementing MBSE in SMEs.

Keywords: model-based systems engineering, small and medium-sized enterprises, MBSE adoption, MBSE implementation.

JEL Classification: L21, L22, M1, O31.

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Introduction

Systems Engineering (SE) dates back to the 1940s when the United States Department of Defence used it to develop missile systems (Goode et al., 1957). In the late 1950s, the RAND corporation also applied system analysis, which later became part of the SE technical processes to develop the system's logical architecture. The inception of SE started in the realm of large corporations, but as subcontractors of these large corporations, Small and Medium-sized enterprises (SMEs) also stood to benefit from its application (Akundi & Mondragon, 2022).

SE and Model-Based Systems Engineering (MBSE) are cut from the same cloth, but the former is more document-centric and the latter model-centric. Despite being customisable to many disciplines and organisations (Walden et al., 2015), SE is not yet widespread in SMEs

(Gräßler & Hentze, 2018). The general SE approaches have been developed for larger enterprises. They are not suitable for the SME culture that is less documented (Gräßler & Hentze, 2018; O'Connor et al., 2010; O'Connor & Coleman, 2009). SMEs also do not have the financial resources and expertise to implement SE standards such as the EIA 632. Although a standard to guide SE implementation in SMEs has been developed, the ISO/IEC 29110 shows little to no evidence of improvement due to the lack of evaluation research (Galinier & Laporte, 2018; Laporte & Vargas, 2014).

MBSE presents an opportunity to solve some of the problems SMEs face in adopting SE. MBSE is characterised by models used to design, analyse, and manage complex systems. These models have various types, such as functional, behavioural and physical models, that are integrated to capture the systems requirements and system behaviour into the system architecture (Wymore, 2018).

Several methodologies have been presented to aid the transition and adaptation of MBSE in corporations, namely: IBM Telelogic Harmony (Douglass, 2005), the INCOSE Object Oriented Systems Engineering Method (OOSEM) (Lykins et al., 2000), IBM Rational Unified Process® for Systems Engineering for software development projects (Kruchten, 2004), and Vitech MBSE methodology as part of the CORE® suite, among others. The overarching similarity amongst most of the methodologies, besides being developed by and for large corporations, is that they are tool-dependent and therefore require intensive training and tool support before an enterprise can confidently adapt them.

This research, therefore, seeks to investigate SMEs' needs in adopting MBSE and the problems they face through a structured online survey targeting SE professionals and engineers in Southern Africa. The survey results are then used to propose a process framework for adopting MBSE in SMEs with their needs in mind and without single-tool dependence. The following research questions formed the basis of this study.

- Q1. What is the state of SE and MBSE adoption in South Africa?
- Q2. What factors affect the success of MBSE adoption in different enterprises?
- Q3. What framework can improve the uptake of MBSE in SMEs?

1. Systems and model-based systems engineering in SMEs

1.1. Small and medium-sized enterprises

SMEs in South Africa include a broad range of firms, including those formally registered and in-formal non-registered enterprises (Department of Trade and Industry, 2005). By size, they range from medium to survivalist informal businesses. The latter group is characterised by self-employed people from some of the poorest settlements in the nation (Makwara, 2019). They are typically involved in street trading, backyard manufacturing and home-based evening jobs. These enterprises, employing less than 50 individuals, classified as small businesses and micro enterprises in Table 1, are not the subject of this research. SMEs in this research mainly refer to Medium-sized firms which employ upwards of 50 employees, as seen in Table 1.

Table 1. Small Business Initiative (SBI) Classification of Enterprises in South Africa (source: Department of Trade and Industry, 2005)

No. of Person-Year Jobs	Classification
0–10	Micro-Enterprises
11–50	Small Businesses
51–200	Medium-sized Firms
>200	Large Enterprises

SMEs contribute 50–60% of the total employment and 30–40% of the annual GDP in South Africa (Zhou & Zondo, 2023). Unfortunately, many of these enterprises do not survive beyond six months. Schirmer and Visser (2021) list the causes as poor management, the inability to access markets and low funding. The average SME in South Africa is characterised by family ownership because the enterprises were created as a source of personal income (Soni et al., 2015). Financially, there is no formal structure for determining the selling price of their products, so they adopt a cost leadership strategy – gaining a competitive advantage by delivering a service or commodity at the lowest cost (Hit et al., 2016). This is not sustainable because it is highly dependent on economies of scale that are difficult to achieve. Mapila et al. (2014) suggest that these SMEs adopt a focused differentiation strategy – delivering a unique service or product that suits the needs of a niche market. However, this needs efficient market research to understand customer requirements better (Soni et al., 2015). As a result, the strategies adopted by these SMEs are ill-informed, causing the enterprises to fail.

1.2. Systems engineering

SE is a "*transdisciplinary and integrative approach to enable the successful realisation of engineered systems, using systems principles and concepts, and scientific, technological, and management methods*" (Walden et al., 2015). Engineered systems considered within the scope of SE are "*technical or socio-technical systems that are designed or adapted to interact with an anticipated operational environment to achieve one or more intended purposes while complying with applicable constraints*" (Martin, 2022). All systems herein referred to are engineered systems.

Engineered systems are increasingly becoming complex with newer modifications, and SE aims to reduce the risk that comes with these modifications and improvements (Walden et al., 2015). Systems science, which encompasses knowledge areas such as systems thinking, systems approach, and modelling, is the foundation for understanding and creating solutions for complex systems. Technological advancements in today's age are creating an operating environment for most engineered systems that are non-linear and complex with increasing unpredictability (McChrystal et al., 2015; Walden et al., 2015).

Unlike traditional projects with stable requirements, modern systems are one or part of an evolving system of systems (SoS). Developing a modern system requires the collaboration of several experts and disciplines. However, their interdependence and intercommunication are complex (Walden et al., 2015). Therefore, today's system engineer is faced with the task of effectively integrating these disciplines throughout the life cycle of the engineered system. The main SE activities carried out along the lifecycle of the system include (Walden et al., 2015):

- *Requirements Management*. Requirement management involves translating the stakeholder needs and requirements into the system's requirements. A good requirements management process captures and understands stakeholders' needs and views of the system functions.

- *Behavioural Architecture*. The behavioural architecture elicits the high-level functions of the system that satisfy the stakeholder's needs. The external functions captured from the requirements management process model the system's behaviour, including the interactions and elements transferred between the System of Interest (SoI) and its external systems.
- *Physical Architecture*. The behavioural architecture is further broken down such that a single process is assigned to a single element. The interfaces between the elements are defined and modelled. Scenarios are also used to visualise the working of the SoI.
- *Verification and Validation*. The requirements, behaviour and physical architecture are checked against the system's proof (verification). Has the right system been built? Does the system satisfy the stakeholder's needs?

As a foundation of SE, systems thinking recognises interconnections in the system structure and how these facilitate system behaviour (Arnold & Wade, 2015). Therefore, the application of SE processes in SME development will seek to understand the behaviour of the components of the enterprise, how they interact with each other, and the resultant emergent properties. The ideal emergent property is a good bottom line that can be achieved with MBSE adoption in these SMEs, thus improving their chances for success and contribution to the economy.

1.3. Model-based systems engineering

Models employed in MBSE present a clear design that can be well communicated to all stakeholders, including non-professionals, coherently to confirm the need for the system. These models have been formalised into the SE processes to form the foundation for MBSE. MBSE is defined in INCOSE's Systems Engineering Handbook (Walden et al., 2015):

"*...the formalised application of modelling to support system requirements*, *design*, *analysis*, *verification*, *and validation activities from the conceptual design*, *throughout development and other life cycle phases*."

INCOSE adapted the standard series ISO/IEC/IEEE 29110 to aid the application and realisation of the benefits of SE in very small and micro enterprises (Laporte et al., 2016; O'Connor & Laporte, 2017). It is the only official standard for this concern (Gräßler & Hentze, 2018). Amongst the benefits listed by Henderson and Salado (2021) in their literature review on the benefits of MBSE adoption in corporations, the benefits listed in Table 1 directly benefit the status of SMEs in South Africa. Secondly, the progression of the third and fourth industrial revolutions led to the birth of the modern enterprise characterised by digital engineering, data analysis, and artificial intelligence (AI) (Schwab, 2015). Strategically transitioning into a modern enterprise thus requires a company to equip itself with these tools.

MBSE is particularly useful because it is the connective tissue of the SE digital engineering environment in the modern enterprise (Long & Scott, 2012). SMEs that have not equipped themselves in any way for the new age shall be left behind. Adopting MBSE can be a starting point for this transition. Therefore, the researcher's goal is not to overturn the current processes being used by SMEs and adopt the full MBSE ensemble but rather to provide a guided process using SE principles and tools to aid the transition to a digital age.

Table 1. MBSE adoption benefit types (source: Huldt and Stenius, 2019)

Benefit type	Application to SME context
Reduce ambiguity	Streamlining business decisions such as selling price and a record of variable costs based on an informed structure.
Improved system understanding	Better insight into the problem and understanding of customer requirements.
Reduce effort	Reduced engineering effort through the reuse of modelling elements.
Better decision making	Make better-informed decisions by aggregating data on the market and customer needs.
Multiple viewpoints of a model	A more holistic representation of the system of the industry and its partners.
Better communication and information sharing	Improved communication with stakeholders, team, designers, developers, and suppliers.

Owing to most SMEs' poor management skills and structure, the main hurdles to adopting the MBSE approach to systems management are the "lack of a clear organisational structure with an understanding of required conditions and management needs" (Huldt & Stenius, 2019). Secondly, businesses feel that they have made it thus far without the help of a "systems" effort and that it is "over-dimensioned" for their products (Czaja et al., 2016). Deploying MBSE has been noted to be a burdensome process that is not tailored to the needs of the SME culture, resources, skills and tools (Chapurlat & Nastov, 2020). The proposed standards, such as ISO/IEC 29110, and the process to adopt them in SMEs are still too complicated for their business needs (Laporte & Vargas, 2014).

1.4. Recommended best practices for successful adoption

A clear goal and strategy. The engineering activities to be supported by MBSE need to be clear. If this is not done, the adoption effort shall be frustrated, and the returns will be low. The strategy of adopting MBSE could be as a support activity – used with the textual or document-based deliverables or full-on – where the different models are the deliverables at each life cycle stage. The decision by the company on which strategy to implement is as important as the investment (Faudou et al., 2016).

Align SE practices before deploying MBSE. The SE team should be fully aware of the SE's good practices and their definitions and concepts (Faudou et al., 2016). Understanding the model elements and the underlying concepts when working with the different MBSE tools is one of the adoption challenges (Chami & Bruel, 2018). Therefore, ensuring that the team adopting MBSE is aware of the underlying concepts is essential. Training is an excellent solution to this.

Competence and Competence Frameworks. According to the Merriam-Webster dictionary, "*competence*" is "the state of having sufficient knowledge, judgement, and skill for a particular duty." "*Competency*" is a "specific area of competence". A "*Competency Framework*" is a structure that sets out and defines each individual competency required by individuals working in an organisation or part of an organisation (Chartered Institute of Personnel and Development (Great Britain) (CIPD), 2018). Maturity Models identify organisational strengths and weaknesses and provide benchmark information to process information (Khoshgoftar & Osman, 2009). The difference between a competency framework and a maturity model is the target of the analysis. While the competency framework targets individuals in the enterprise, maturity models assess the enterprise's capabilities.

In Systems and Software Engineering, the Capability Maturity Model (CMM) was first proposed in 1990 by the Software Engineering Institute (SEI). In parallel, the Systems Engineering Capability Assessment Model (SECAM) was launched by an INCOSE Working group (Faulconbridge & Ryan, 2003). In 2011, SEI integrated the available models to form the infamous CMMI (Capability Maturity Model Integration). In 2018, the INCOSE International Competency Working Group defined a competency framework for capabilities regarded as central to the practice and profession of SE. The INCOSE Competency Framework provides a set of 36 competencies for SE within a tailorable framework that provides guidance to identify capabilities crucial to the effectiveness of SE. Using the competencies listed, practitioners create models tailored to the needs of their enterprises. As noted in the best practices for adopting MBSE, the SE team must be competent in the fundamentals of SE as a discipline. Therefore, competency assessment ensures that the correct skill set is available to apply and utilise the MBSE in the enterprise.

An aggregation of the encountered problems and the recommended best practices or success attributes from the literature forms the starting point for investigating the adoption of MBSE in SMEs in South Africa. In proposing an adoption framework for SMEs in South Africa, an investigation of the current situation and specialities surrounding the SE/MBSE landscape was necessary. These hindrances are then compared against some recommended best practices to justify the adoption landscape's state. The following section elicits the inquiry method and the investigated factors' development.

2. Method

The survey methods employed to fulfil the research objectives include a literature survey and an online questionnaire survey. The main aim of the preliminary literature survey was to capture the current state of SE/MBSE use in engineering-based industries in South Africa and explore the following aspects.

- The problems facing SMEs in South Africa.
- The attributes of global MBSE adoption practices and how they are compared to the ones recorded in South Africa.
- Case studies of MBSE implementation in other industries/countries worldwide.

A literature survey is a probe for obtaining secondary data (Easterby-Smith et al., 2021). The literature survey herein was also used to explore aspects of MBSE adoption previously explored and tailor them henceforth for newer insights in a different geographic and economic context.

The primary role of an inferential survey is to establish relationships between variables and concepts (Easterby-Smith et al., 2021). This survey aims to accurately map the landscape of MBSE adoption in Southern Africa and explore its benefits to the different enterprises. From this, a set of predictor variables can be isolated to explain the extent of adopting MBSE.

This relationship shall, after that, be used to design the MBSE-Lite framework. The tool of choice is an online questionnaire created using Google Forms. The questionnaire captured demography characteristics such as location, the company sector and how many individuals are employed to classify the respondents into large enterprises or SMEs. The questionnaire took the respondent to different sections depending on their exposure to SE or MBSE using automated skip logic with conditional questions. This reduced item nonresponse and an unnecessary burden to the respondents to whom some questions did not apply (Peytchev et al., 2006). Five experts in the field performed pre-testing.

The research was conducted in South Africa. The population of formal SMEs in South Africa is 17,397, according to Schirmer and Visser (2021). It is challenging in such a population to determine the SMEs using SE and those that are not; time restrictions would not allow that. Since an accurate sample size could not be accurately estimated, snowballing, a non-probability sampling technique, was used to send out the surveys (Easterby-Smith et al., 2021). Three separate sets of samples were targeted; professional filters on LinkedIn, the INCOSE-SA mailing list, and the University of Pretoria at the Faculty of Engineering and Built Environment Alumni.

2.1. Survey

The survey was conducted over two months using a structured Google Form that was separated into three major sections, an introductory section that characterised the enterprise within which the respondent worked by size, their role in this company, their academic level and their perceived expertise in SE using the five levels of the INCOSE Maturity Framework (Gelosh et al., 2014), an intermediary section that assessed their use of traditional SE, their perception of its success and its perceived benefits, and the last and most important section addressed the adoption of MBSE from the viewpoint of respondents that had not heard about it or used it before as well as those who had been using it.

The MBSE success attributes that were investigated include a clear goal and strategy (Holt, 2017; Pratt & Dabkowski, 2022), Management support and cooperation (Amorim et al., 2019; Pratt & Dabkowski, 2022; Vogelsang et al., 2017), Human Resource upskilling (Amorim et al., 2019; Holt, 2017; Pratt & Dabkowski, 2022), and alignment of company practices to SE practices (organisational support) (Pratt & Dabkowski, 2022).

The challenges associated with MBSE adoption that were identified from the literature and investigated in the survey include an expensive initial investment and tool (Chami & Bruel, 2018; Czaja et al., 2016; Gregory et al., 2020; Pratt & Dabkowski, 2022), the human factor that includes training and the presence of the right expertise on MBSE undertakings (Czaja et al., 2016; Ferguson et al., 2020; Pratt & Dabkowski, 2022; Suryadevara & Tiwari, 2018), inertia in the enterprise that stems from existing legacy methods and norms (Czaja et al., 2016; Gregory et al., 2020; Pratt & Dabkowski, 2022), as well as whether the selected tool for implementation was the problem regarding upfront cost, dependency and integration (Kass & Kolozs, 2016; Savary-Leblanc et al., 2021). Select success attributes from the survey were then investigated to determine their correlation to MBSE success in SMEs.

3. Results

3.1. Sample characteristics

The total number of respondents answering all questions was 105, including engineers and SE professionals across different industries. The main attributes used to characterise the sample are the company's size, determined by the number of full-time employees and their level of SE awareness. The results of this characterisation are presented in Figure 1 and Figure 2 below.

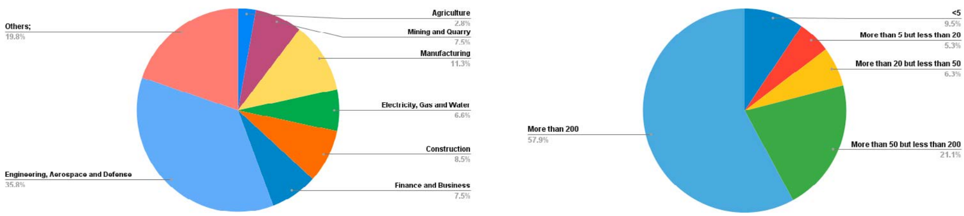

Figure 1. Industrial sector and company size distribution findings from the respondents

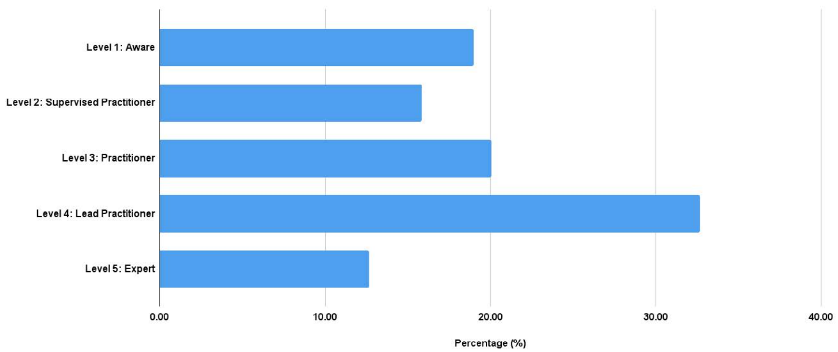

Figure 2. SE competence levels of the correspondents

3.2. SE/MBSE implementation landscape

A total of 107 responses were collected from the alumni of the engineering faculty at the University of Pretoria, select SE practitioners through LinkedIn and members of INCOSE South Africa. These responses were further categorised by size into large enterprises and SMEs to form a parting point for characterising the SE/MBSE landscape. The presence of MBSE was compared with the preceding presence of SE in the enterprise in Figure 3. Analysis was done later to prove the correlation and whether it contributed to the latter's success. It is a good point of departure that most enterprises using SE have transitioned to MBSE, and it is therefore not a surprise that the enterprises without traditional SE do not have MBSE. Only three such cases were captured.

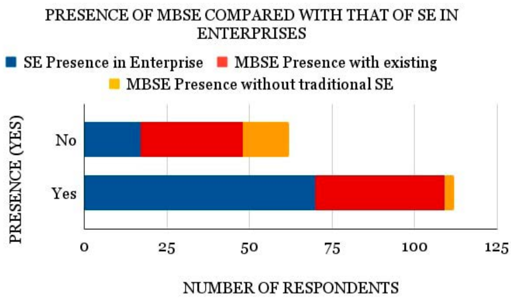

Figure 3. SE/MBSE presence in the enterprises

Since one of the research objectives is to identify elements of the MBSE implementation process that can be tailored into a framework, assessing the success already achieved was also important. 80% of the enterprises that have transitioned to MBSE consider it successful. The 20% that report it unsuccessful attribute it to:

- The technology is unknown and/or applied in their fields, such as IT and Data Analytics. Respondents in the industrial engineering sector reported the presence of other methodologies that achieve the same goal.
- Having never heard of it and that it is unknown in their organisations.
- The simplicity of the systems on which they work does not require SE.
- The fear is that it may be expensive to implement.

3.3. MBSE implementation landscape in SMEs

The responses from SMEs were 47% of the 105 captured. 76.5% of these reported using traditional SE, but only 23.5% had started a transition to MBSE, as shown in Figure 4 below. At this point, it is important to note that the enterprises in which MBSE is in use report success save for a few difficulties, such as management support and MBSE tool integration. Statistical inferences were then employed to dissect and understand this reported success.

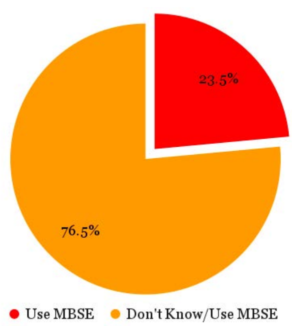

Figure 4. Percentage of SMEs employing MBSE

It was analysed from the survey as the dependent variable and investigated using other independent variables such as the presence of training, the age of MBSE and if it has been implemented with the prior presence of traditional SE. A dissection of this comparison in Figure 5 reveals that the SMEs using MBSE are doing so without training. A considerable effort has been invested because the more significant number has been trying to integrate it for over three years. Further statistical analysis of these variables was done to infer the predictors of successful MBSE integration in the following section.

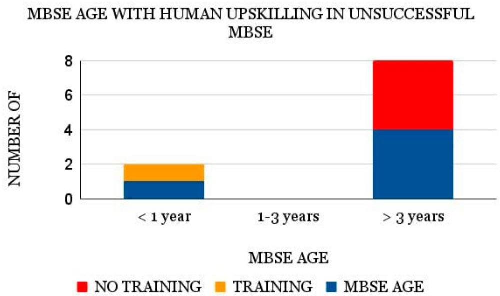

Figure 5. Unsuccessful MBSE in SMEs, MBSE age versus human upskilling

3.4. Bivariate correlation analysis results

Since the analysis's objective is comparing different variables and their correlation with the success of MBSE in enterprises (n_MBSE_SUCCESS), these were checked using bi-variate correlation analysis. The independent variables explored include; Presence of training in the enterprise (n_MBSE_TRAINING), the period over which MBSE has been in use (n_MBSE_YRS) and whether or not MBSE was adopted in the presence of traditional SE (n_MBSE_PRESENCE_noSE & n_MBSE_PRESENCE_wthSE).

A strong correlation exists between n_MBSE_SUCCESS and n_MBSE_TRAINING at 0.606 and a sounding significance <0.001. n_MBSE_YRS and n_MBSE_PRESENCE_noSE have a close to non-existent correlation to n_MBSE_SUCCESS and are also insignificant at 0.628 and 0.859, respectively. n_MBSE_PRESENCE_wthSE, on the other hand, has a strong positive correlation with n_MBSE_SUCCESS at a value of 0.796 and a significance <0.001. The results from this analysis are shown in Appendix.

3.5. Multiple regression analysis results

A multiple regression analysis was run to predict the success of MBSE using training and the presence of traditional SE in the organisation. These variables statistically predicted MBSE success, $F(3, 90) = 69.099$, $p < 0.001$, $R2 = 0.687$. All variables at $p < 0.001$ were statistically significant, except no MBSE at $p < 0.167$. This indicates that MBSE training and its introduction with the presence of traditional SE are accurate predictors of the success of MBSE in that enterprise. The results from the regression analysis are shown in Appendix.

3.6. Data reliability

Cronbach alpha was used to measure the internal consistency of the results from the regression analysis. Since multiple variables have been used to form composite scales, it is essential to ensure that the same underlying construct is being measured. The results for the reliability analysis of the variables (5 No.) returned a Cronbach's alpha of .677. The cut-off value for a reliable Cronbach's alpha is 0.7, but a value of at least 0.6 is acceptable (Hair Jr et al., 2017; Nagpal et al., 2010).

4. Discussion

The data confirms the literature suggesting the benefits of SE and MBSE in organisations that have adopted them. However, the transition to MBSE in both large enterprises and SMEs is lower than expected or completely unsuccessful in the latter's case. The data further supports the literature that the uptake of MBSE by SMEs is very low. While the enterprises using it are well aware of the benefits, they have not yet realised them. The following section discusses the results in the context of the study's research questions.

4.1. Research question 1: state of MBSE and SE adoption in South Africa

The data indicate that SE is more prevalent in the Engineering, Aerospace and Defence sector in large and medium enterprises and SMEs. In contrast, the rest of the industry sectors are unaware of how SE applies to their industries. Surprisingly, all respondents reported at least Level 1 awareness of SE but were not ably supported to use it in the workplace or were completely unaware of how to do so.

Enterprises already using SE show an excellent transition to MBSE across the landscape. The data has also revealed that it is a rare case for an enterprise to successfully apply MBSE without implementing traditional SE. The awareness of traditional practices fosters the appreciation of the simplicity of transferring to the digital paradigm. SMEs have shown initiative to employ MBSE in their operations, but all of them report failed to do so. The data shows that the tools used to implement MBSE are not MBSE tools. This is an indicator that MBSE and SE are still not widely understood. Respondents have indicated awareness of SE and its practices, but as is the case for SMEs, all respondents who report using MBSE have not received any training.

4.2. Research question 2: factors that affect MBSE success

The data essentially suggested that training and the MBSE tool of choice were significant determinants of the success of MBSE in enterprises. Results from the data's correlation and multiple regression analysis further confirmed this. In addition, adopting SE is a strong predictor for MBSE success in the enterprise. While it was impossible to form such predictions from the tools collected from the survey, the appearance of "wrong" tools in datasets that returned MBSE as unsuccessful was an indicator that the use of the right tool is a gateway to a smooth adoption process.

The bivariate correlation analysis of the independent variables indicated the presence of training, age of MBSE in the enterprise, and presence of traditional SE as significant to the success of MBSE. Therefore, in implementing MBSE, care should address training in the nascent stages. If traditional SE was not present, foundational training on Systems sciences should be deployed before the plan to introduce MBSE. Failure to do this has indicated that the plans to reap the benefits of MBSE in the enterprise shall be futile. This is in agreement with the best practices laid out in (Holt, 2017), where the assessment of the employees' competencies of the enterprise is the first good practice for MBSE implementation.

4.3. Research question 3: how the elements of the proposed framework shall aid MBSE uptake in SMEs?

With the landscape of SE and MBSE adoption and the predictors for the success of MBSE adoption now clear, the MBSE-Lite framework presented a process to guide the introduction of MBSE in SMEs, as seen in Figure 6. The MBSE-Lite framework encompasses both the technical aspects of SE modelling and its financial and decision-making inputs by creating a communication link between the enterprise repository of the organisation and its model repository. Besides guiding the technical MBSE Process, the framework shows the linkages of the benefits of MBSE realised through its implementation (shown in orange blocks). It has three main high-level blocks: the Enter-prise repository, the MBSE Process, and the Model Repository.

The Model Repository is the logical or physical storage space for all the modelling elements along the SoI's system lifecycle (Fisher et al., 2014). It also includes previously developed systems and their corresponding elements and views.

The Enterprise Repository on the far right of the model includes the necessary enterprise documentation to be included in the implementation project. The documents included are based on the business model elements, including processes, policies, projects, and software libraries. It is a point of definition for all the enterprise resources. The assumption is that when model-ling is done in light of the enterprise's strategic choices, value creation and network, it is done while keeping the target customer in mind. Communication with these documents directly aids resource management and communication for reuse. Data used for implementing one project, for example, pricing, can then be directly applied to another modelling project. The MBSE process in the framework captures a high-level view of the modelling process that an enterprise can follow to manage complexity and understand its customer requirements.

The MBSE Process is the spine of the network that forms the MBSE-Lite framework. It captures the technical SE processes necessary for modelling the SoI from concept development to handover to the client. The step-by-step execution is described in the following paragraphs.

- *Needs Capture*. This framework phase represents the capture of the client's needs in the form of documents, models, interviews, and any other method seen fit. If obtained as documents, they may be added to the company repository in the model. Compliant with MBSE methodology, the client's needs may be captured in the form of use cases of the functions they envision the SoI accomplishing.
- *SoI Requirements Capture*. This vital step forms the bulk of the requirements engineering phase. Since understanding customer requirements is essential for market capture, it

also stands that translation of their needs into a system that satisfies them is equally important for the same goal. The use case diagrams depict scenarios in which the SoI executes its functions, after which these are analysed. Iteration is done back and forth with the client at this stage for validation. Architectural development ensues afterwards. Details of these steps are described in the paragraphs that follow.

- *Architecture Development*. Compliant with SE terminology, the architecture of the SoI represents how the system shall be implemented. The system architecture is modelled using Functional Analysis. This is done incrementally with the SoI's decomposition and the physical design's development (Long & Scott, 2012).
- *Construction and Integration*, Verification and Validation (IVV). This step may occur simultaneously and iteratively, as presented in the framework. Construction and integration are accompanied by validation/verification tests to ensure that the system being developed complies with the system requirements earlier specified. After the necessary tests and the client's approval of the system, it is handed over with the necessary documentation, such as a user and maintenance manual.

The power advantage of this proposed framework is the interaction among the three main blocks. The enterprise repository informs the MBSE Process through the model repository and vice versa. These connections further highlight how the problems cited in the literature can be addressed by adapting this process framework. The main SME problems of competition, market access, efficient resource management and managing complexity are countered through the MBSE process and the intercommunication between the Model Repository and the Enterprise Repository. By storing subsystem models, the development process of similar projects can be significantly reduced, leading to a shorter time to market.

Robust communication systems are one of the three pillars of incremental innovation that is an asset in small engineering organisations. In this framework, the reuse and interoperability

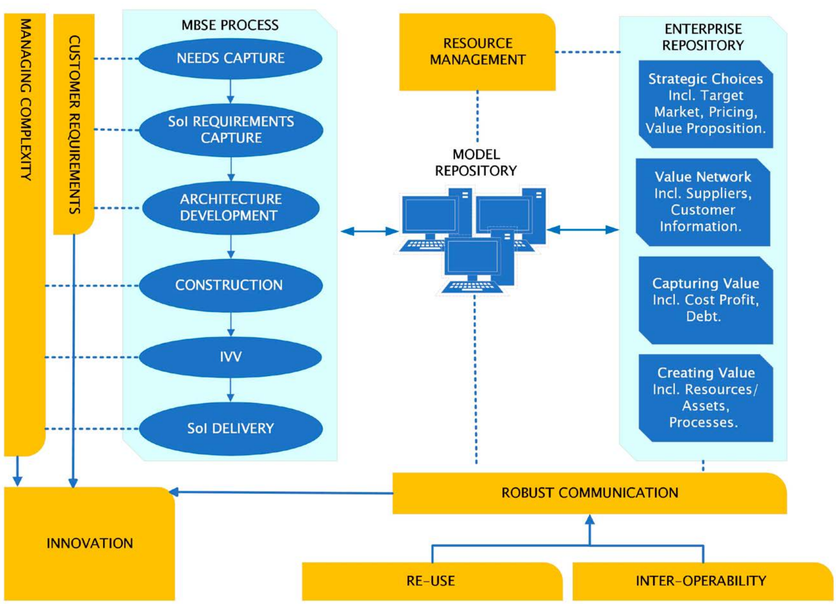

Figure 6. A diagrammatic representation of the MBSE-lite framework

of the developed models support communication between the enterprise and the model repository. The aggregation of understanding customer requirements, managing complexity, and communication is the innovation that is essential to an enterprise looking to leverage competition and enter crowded markets.

The SE and MBSE adoption landscape across industries in South Africa is well behind that in other developed economies. At the same time, it is essential to note that the enterprises that have adopted MBSE and SE have realised the benefits over time. However, SMEs are still in the dark about the potential application of SE in their fields. The MBSE-Lite Framework emphasises training and SE/MBSE awareness before implementation. Complete knowledge of the roots of SE and its complementing disciplines, such as Systems Thinking, is necessary for the appreciation of the value of the discipline. Despite the university education received by many engineers and managers, the industry practice in the discipline is lacking. This has been well attributed to the lack of management support in the different organisations that also do not see the value of employing SE/MBSE in the first place.

A significant advantage of employing MBSE in the enterprise is using meta-models and templates of repeat tasks that cut short the production time of future jobs. The Model Repository is an archive of all the models of previous and current subsystems created on previous projects. For reuse, these models may be retrieved and re-purposed for similar projects. The linkage between this and the enterprise repository links the company's strategy to the products it delivers. A cap on product market price informs its cost price and, therefore, the material that shall be used in its production. This way, the traceability between stakeholder requirements, design decisions and delivered products can be linked to the business/organisational management aspects.

Conclusions and recommendations

The objectives of this study were to explore the landscape of SE and MBSE adoption across different industries in South Africa and develop a framework for implementing MBSE in SMEs, especially those in South Africa. Recalling the objectives is necessary to paint a whole picture of the research context.

The landscape descriptors included the industry type, company size, SE skill level, and the presence/absence of MBSE/SE. SE/MBSE is widely used in the engineering, aerospace and defence industries. Limited distribution is seen in other industries such as construction, finance and business, manufacturing, mining and quarry, petroleum and gas. The skill level of most of the respondents was more significant than Level 3, indicating that a great majority can practice SE without supervision. However, this is not reflected in the presence of SE in their enterprises. SE is used in many large enterprises which have transitioned to MBSE for over three years. The SMEs using SE have transitioned to MBSE but are struggling and have already deemed it unsuccessful.

SE is poorly understood from the data, and the underlying principles necessary for implementation and application are missing. Statistical analysis has proven that training and introducing MBSE in the presence of SE are the main predictors of the successful adoption of MBSE in these enterprises. It is no wonder that SMEs lacking training have not been successful yet. Furthermore, the enterprises that have applied MBSE and are successful have attested to the benefits. SMEs, therefore, need ample guidance during the implementation process. The developed model/framework, MBSE-Lite, seeks to achieve this. With prerequisite training and a guided technical process, SMEs can apply MBSE with their tool of choice.

The available data on MBSE and its adoption in different industries does not capture its progress in developing economies like South Africa. This research has attempted to close that gap by exploring the characteristics pertinent to the technology. In addition, it has revealed some gaps that explain why the transition has taken so long. Professionals and academia can fill these gaps in drafting training and education plans for future engineers. Systems science has tremendous application potential, and its soft methodologies, when coupled with other sciences, can make great strides in achieving "whole" objectives, especially in complexity management.

Study limitations

The primary study limitation was the population reached. It was impossible to determine the SMEs employing SE/MBSE. It is for this reason that a snowballing sampling approach was used. Refined results can be obtained by targeting enterprises where SE already exists and respondents know its potential application. Secondly, the study was limited by time. A more significant sample space of SMEs can be reached with more time. This, however, does not take away from the strength and validity of the results presented herein.

Recommendations for future research

This study has proposed a model/framework for implementing MBSE in SMEs. Future research should look into a case study or evaluation research of its application in a select SME and its consequent validation.

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APPENDIX

Bivariate correlation and multiple regression analysis for MBSE success in the enterprise

Table A1. Bivariate correlation analysis between human upskilling and MBSE success

		n_MBSE_SUCCESS	n_MBSE_TRAINING
n_MBSE_SUCCESS	Pearson Correlation	1	.606**
	Sig. (2-tailed)		<.001
	N	94	94
n_MBSE_TRAINING	Pearson Correlation	.606**	1
	Sig. (2-tailed)	<.001	
	N	94	94

Note: ** Correlation is significant at the 0.01 level (2-tailed).

Table A2. Bivariate correlation analysis between MBSE age in the enterprise and its success

		n_MBSE_SUCCESS	n_MBSE_YRS
n_MBSE_SUCCESS	Pearson Correlation	1	.073
	Sig. (2-tailed)		.628
	N	47	47
n_MBSE_YRS	Pearson Correlation	.073	1
	Sig. (2-tailed)	.628	
	N	47	47

Note: ** Correlation is significant at the 0.01 level (2-tailed).

Table A3. Bivariate correlation analysis between the presence and absence of SE and MBSE success in the enterprise

		n_MBSE_ SUCCESS	n_MBSE_PRESENCE_ withSE	n_MBSE_PRESENCE_ noSE
n_MBSE_SUCCESS	Pearson Correlation	1	.0796**	–.019
	Sig. (2-tailed)		<.001	.859
	N	94	94	94
n_MBSE_ PRESENCE_withSE	Pearson Correlation	.0796**	1	–.170
	Sig. (2-tailed)	<.001		.101
	N	94	94	94
n_MBSE_ PRESENCE_noSE	Pearson Correlation	–.019	–.170	1
	Sig. (2-tailed)	.859	.101	
	N	94	94	94

Note: ** Correlation is significant at the 0.01 level (2-tailed).

Table A4. Model summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.835[a]	.697	.687	.27334

Note: [a] Predictors: (Constant), n_MBSE_TRAINING, n_MBSE_PRESENCE_noSE, n_MBSE_PRESENCE_wthSE.

Table A5. ANOVA [a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15.488	3	5.163	69.099	<.001b
	Residual	6.724	90	.075		
	Total	22.213	93			

Note: [a] Dependent Variable: n_MBSE_SUCCESS; [b] Predictors: (Constant), n_MBSE_TRAINING, n_MBSE_PRESENCE_noSE, n_MBSE_PRESENCE_wthSE.

Table A6. Coefficients [a]

Model		Unstandardised coefficients		Standardised coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	2.776E-16	.040		.000	1.000
	n_MBSE_PRESENCE_noSE	.230	.165	.083	1.394	.167
	n_MBSE_PRESENCE_wthSE	.662	.067	.679	9.859	<.001
	n_MBSE_TRAINING	.310	.081	.261	3.839	<.001

Note: [a] Dependent Variable: n_MBSE_SUCCESS.