Technology Roadmapping and Systems Engineering - A Symbiotic Relationship?

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Abstract. Recent advances in technologies have changed how we live, conduct business, and interact with each other. Moreover, these advances have given rise to new complex systems and systems of systems. As the complexity of systems increases, new and innovative strategies and management techniques are required to cope. Systems Engineering (SE) and Portfolio Management have been employed to manage such complexity in systems development, while Technology Roadmaps (TRM) have been used for strategic Technology Management. This article explores the symbiotic relationship between SE processes, Systems Thinking (ST) tools and TM, specifically TRM. The objective is to emphasise SE's and ST's role in TM processes and vice versa. It is postulated that TRM can be used as data for SE processes, while some SE processes can be used as tools in the TRM processes.

Introduction

Recent advances in technologies have changed the way we live, conduct business, and interact with each other. Moreover, these advances have given rise to new complex systems and systems of systems. It is said that the Fourth Industrial Revolution (4IR) will have a disruptive impact on every establishment, government, organisation, industry, sector, and on our social interactions. Driven by new and emerging technologies, 4IR requires organisations to transform their production, management, and governance of systems to cope with these disruptions. Therefore, new business and technology strategies will need to be developed (Schwab 2015).

Robert Phaal, Farrukh, & Probert (2004) argued that “effective management of technology is important if firms are to cope with the challenges of emerging technologies, rapidly changing market conditions, globalization and the growth of developing economies”. This also implies that for effective Technology Management (TM) and for organisations to be competitive in this technology-driven era, they require new and innovative ways of doing business, including thinking, planning, and managing capability. Therefore, organisations must develop technology and business management strategies to compete and take advantage of these emerging technological capabilities for optimal business performance (Phaal et al., 2012; Probert, 2012).

Cetindamar, Phaal & Probert (2016) have proposed TM methods, activities, processes, supporting tools and a framework for strategic TM. TM tools and processes such as technology roadmaps and roadmapping have been used in many industries and sectors as a framework for strategic technology planning. The flexibility of a technology roadmap (TRM) enabled it to be used in the context of technology evolution and revolution (Phaal, Farrukh & Probert 2004).

Although TRMs are versatile in their usage for strategic TM, the construction of a roadmap is not a simple activity. It involves identifying, selecting, adapting, and integrating a number of TM tools. Using TM tools seamlessly with the processes and systems of the organisation for the management of technology may not be an easy task (Kerr et al. 2013). This problem is exacerbated by the decision-making activities that usually accompany the development of a TRM, which requires statistically robust and academically sound methods, techniques and supporting tools. Robert Phaal et al. (2012) emphasized that the focus areas of strategic TM are informed decisions about technology investments and planning of deployment.

Systems Engineering (SE), Systems Thinking (ST) and other management (e.g. Portfolio Management (Specking, Parnell & Pohl 2020)) practices have also been employed to cope with systems complexities. SE tools have been adapted to the construction phase of a TRM (Golkar & Garzaniti 2020; Gradini et al. 2019). ST tools may also be applied to support understanding of the impact that the new technologies have on the existing systems in the operational environment.

This paper explores the relationship between ST in SE and TM, focusing on the TRM phases (not only the construction phase). The research in this paper is in the form of an exploratory literature review to identify the relationships between the three fields for improved planning of new technology implementation. These relationships are captured in a systemigram, a ST tool, to improve the understanding of the symbiotic relationship between SE and TRM. This is the starting point for in-depth research about the synergies between ST, SE, and TM.

Systems Engineering

Overview

The International Council on Systems Engineering (INCOSE) Handbook defines SE as "an interdisciplinary approach and means to enable the realisation of successful systems" (Walden et al. 2015). SE is a multidisciplinary profession, process, and perspective that considers the whole system instead of only its parts in isolation. SE employs an approach that defines customer needs and requirements before specifying, designing, and validating a solution system. The SE effort integrates multiple speciality disciplines that proceed from defining a system's concept solution to production and operation. The SE process considers a solution system' life cycle, function, structure, behaviour, and performance characteristics. As the complexity of problems increases, so does the need to implement SE to develop a solution (Walden et al. 2015).

As shown in Figure 1, a basic SE process analyses stakeholders needs within the context and environment characteristics to define requirements and develop possible solution concepts (US Department of Defence, 2001). The process takes stakeholder needs as input to derive requirements through analysis. A functional analysis processes the requirements to propose an architecture of the solution system for synthesis into a design. In reality, the analysis of the problem is often neglected before offering a solution to be implemented (Walden et al. 2015). Throughout the process, the systems engineer has to capture and validate requirements by interacting with stakeholders. After that, trade-off studies compare the alternative solutions for the best fit to the system and stakeholder requirements. It is clear that throughout the SE process, many disciplines, engineering and others, have to integrate and cooperate to cover the whole problem and solution space (Walden et al. 2015).

Often, the initial steps of the SE process focus on problem definition, requirements extraction, and concept solution development. This forms the motivation and foundation of system development. The output of this initial step is a high-level system description focussing on the main functionalities required. The System Description identifies stakeholders and lists their needs that validate the derived system requirements. An Operational Concept then defines how the user intends to use and support the solution system through operational scenarios. These artefacts support exploring alternative concepts and influence the initial architecture design to ensure that the solution system is being developed for the problem. However, the wrong solution or will be of limited use, even if perfectly implemented.

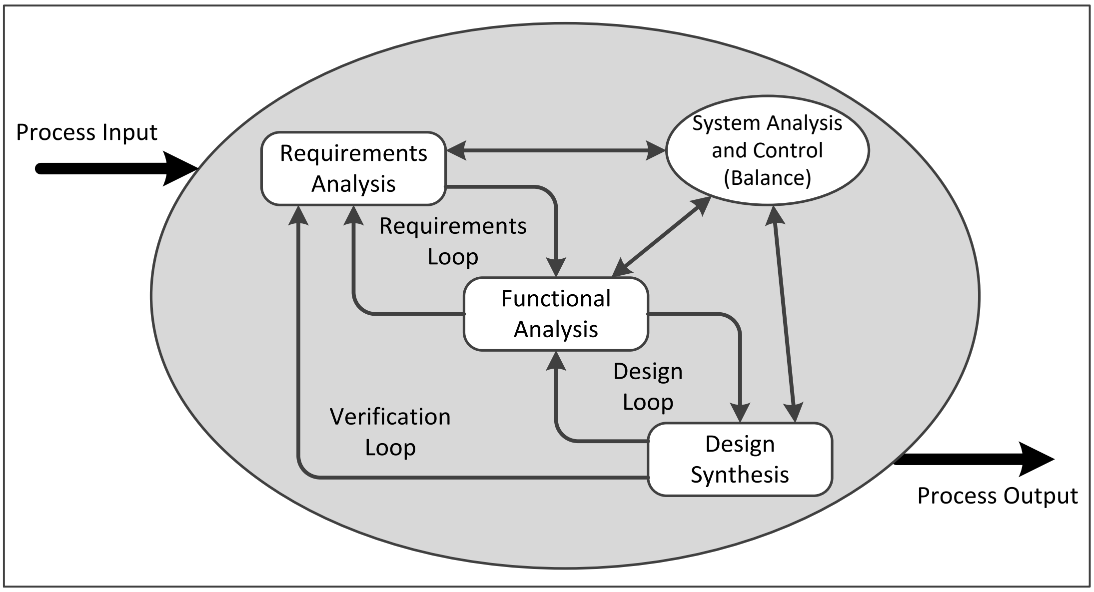

Figure 1: The Systems Engineering Process (US Department of Defence 2001)

System boundaries help us understand what is inside the system and what is outside the system. These can include geographic boundaries, organizational boundaries, physical boundaries, conceptual boundaries (purpose, rules, goals), natural or human-made. A boundary differentiates what is relevant, important, and worthwhile to be part of the system and who benefits. A systems perspective includes the world view and the stakeholders' purpose and their concerns. The stakeholders include anybody or anything with a legitimate interest in the problem or system. However, different stakeholders may have different and even contradictory needs for the solution system.

The systems perspective also addresses the interrelationships between elements within the “whole” system and its environment. The aim is to understand the interconnectedness of elements and the consequences of these connections. Typical connections include funding flows, information flows, or client information. However, system complexity is continually increasing due to globalisation of the marketplace, erosion of trade barriers, reduction of product development cycles, software being part of all new products, reuse of components, and partnerships for product development with worldwide teams. Therefore, SE is a practical approach to help manage complexity (Stevens 1998).

An appropriately implemented modelling approach will aid requirements extraction, developing specifications, designing the solution system, and aiding stakeholders to agree. A model developed in a data-based software tool will help to maintain consistency and traceability between different views and diagrams. These models are also useful to define, extend, refine and validate the system over the total lifecycle (Walden et al. 2015).

Model-based System Engineering

Model-based Systems Engineering (MBSE) is defined as the formalized application of models to perform the SE as discussed above. In particular, MBSE focuses on modelling supported by suitable methodologies, architectures, and software tools instead of text-based document SE artefacts. MBSE processes develop and increase the detail in models to support communication with stakeholders'

(Estefan 2007). The basic MBSE approach is consistent with typical SE “Vee” and may include the following activities (Walden et al. 2015):

- **Stakeholder Needs Analysis.** Causal analysis techniques with scenarios in the form of use cases capture the mission and organisation functionality. The process focuses on the limitations and “as-is” systems to highlight potential improvement areas required of the “to-be” solution.

- **System Requirements Definition.** The modelling activities also defines the system requirements that will satisfy the stakeholder and mission requirements. Black-box modelling also identifies external systems and users as a source of interface, functional, data, and performance requirements.

- **Logical Architecture Definition.** Modelling activities partition and decompose the system is into interacting logical elements able to satisfy the system requirements from the previous step. The logical elements represent the functionality of the system.

- **Design Synthesis of Allocated Architectures.** The relationships among the physical system elements define the distribution of resources throughout the system. Here the concept solution becomes more evident.

- **Optimise and Evaluate Alternatives.** Parametric models that contain performance, reliability, availability requirements of the system guide the selection of the preferred architecture.

- **System Validation and Verification.** The system models enable the systems engineers to verify the system design to ensure it satisfies requirements. Similarly, the models are validated to ensure that the stakeholder needs are satisfied.

SysML or UML are modelling languages for MBSE to capture, analyse, and specify a complex system with its elements accurately with consistent system views. SysML views include system structure, parametric, requirements, and behaviour diagrams. The structural diagrams in SysML represent the system elements and their logical relationships. The SysML behavioural diagrams capture the system activities and their causal interactions. Parametric views provide the system parameters that specify physical, reliability, and performance characteristics (Walden et al. 2015).

Complex Systems Engineering

Classic SE approaches tend to struggle with complex environments and Socio-Technical Systems (STS). They are more suited for the development of narrow and well-defined problems. Therefore, rigidly implementing a standard SE process does not guarantee a successful solution system design, development, and implementation. However, the complex environments are placing ever-increasing demands on SE to produce effective solution systems.

Therefore, Holt & Perry (2008) identified communication, understanding, and complexity as the three evils in performing SE. The total number of system elements, along with their interactions, increase the level of complexity in the system. Not understanding the problem properly and user needs in-depth may lead to capturing inaccurate requirements. Lastly, ineffective communication amongst engineers of the development team and stakeholders may lead to incorrect interpretations of requirements and models.

Complex SE provides alternative approaches for SE to assist in addressing problems with increasing complexity (Kuras 2006). While classic SE focuses on the order in systems, Complex SE tries to affect certain system characteristics to produce the desired results. This is achieved through investigating and analysing evolutionary behaviour in existing systems (Sheard & Mostashari 2009). Complex SE focuses on the system's coherence as a whole without immediate attention to the detail in the system elements. Contrary to this, classic SE tends to focus on the detailed functionality and the implementation of the system. A key step is recognising the complexity in a system and determining when to apply complex SE instead of forcing a classic SE approach to resolve the problem situation. Therefore, Complex SE may revert to ST (soft system) approaches to provide a wider focus than only the technical (hard system) aspects. Literature from various researchers can be summarised into the following list of the guiding principles for Complex SE (Sheard & Mostashari 2009, Kuras 2006, Bar-Yam 2003, White 2010, Rouse 2007, Walker et al. 2009):

- Complex systems must be enabled to evolve into the form required by stakeholders from flexible, vague, and unstable requirements. Attempting to design a system of such irreducible complexity from scratch may be impossible. The system must change (evolve) along with the environment and other changes while maintaining safety and robustness characteristics.

- The system design must retain multiple possibilities of system structure and behaviour while the elements co-evolve with its human users. A tasks analysis must assist the integration of new technology in providing flexible, transparent, simple, and open system elements where humans may maintain self-synchronisation and flexibility to perform real-life, complex, and effects-based tasks.

- Complex SE focuses on human behaviour, such as performance, mental models, and social networks, in a complex world. Different humans have various skills, cognitive capabilities, and experiences that may cause non-deterministic behaviour in the system functions under ever-changing conditions. Information-age systems enable humans to perform multiple tasks with the same technical system, achieving the same end-states from different initial conditions.

- Complex systems require a multi-scale analysis to understand the system for planning adjustments. The analysis should include the system development, acquisition, and operation context.

- System design should focus on the elements that causing complexity. The system elements causing local actions that can influence global behaviour should be identified.

Systems Thinking

As the complexity of our world increases, ST is emerging as a critical factor for success (Bala, Arshad & Noh 2017). ST can be defined as a system of thinking about complex systems. It tries to simplify reality to enable dealing with it more effectively. ST provides a powerful language for representing and operationalizing the mental models of the system's stakeholders (Von Kutzschenbach & Brønn 2017). Several definitions exist for Systems Thinking. However, some of the popular versions include (Arnold & Wade 2015) (Senge 1990) (Sterman 2000) (Sweeney & Sterman 2000):

- The art and science of making reliable inferences about behaviour by understanding the underlying structure.

- A discipline for seeing wholes and a framework for seeing interrelationships rather than things.

- A philosophy, methodology, perspective, language, and set of tools for understanding behaviour of complex dynamic systems.

- Holistic (integrative) versus analytic (dissective) thinking.

ST helps to understand better the deep roots of complex behaviours derived from the underlying patterns and structures to predict them better and, ultimately, adjust their outcomes. Therefore, ST enables solving complex problems where reductionist thinking tends to fail. An ST approach consists of synergistic analytic skills to improve understanding systems, predicting their behaviours, and devising modifications to produce desired effects. This includes capturing stakeholders' mental models and simulating them to draw conclusions and make decisions (Arnold & Wade 2015). As with most systems, ST considers the elements or variables in a system, their relationships (inter-connections) and the function, purpose, or goal to be achieved (Monat & Gannon 2015).

Behaviours derive from the structure with a focus on relationships and causal feedback loops. The core principle of systems thinking is that true understanding of a system lies in the system's structure and the causal relationships between system parameters. A reductionist approach attempts to reduce the whole to its constituent parts, looking for hierarchical relationships and identifying linear causality. Unfortunately, in a world with complex problems and many different variables, the multiple dynamic relationships cannot be defined linearly (Cabrera & Cabrera 2015).

As a holistic approach, ST focuses on the system as a whole to study the structures and behaviours while considering the linear or nonlinear interaction of the parts. The output aims to explain emergent behaviours of complex systems with seemingly illogical behaviours (Monat & Gannon 2015). ST recognises feedback's role in a complex system instead of only focusing on linear relationships (Turpin & Alexander 2014; Von Kutzschenbach & Brønn 2017; Monat & Gannon 2015; Arnold & Wade 2015).

Technology Management

Overview

Cetindamar et al. (2016) defines TM as management that consists of activities that "include planning, directing, controlling and coordinating the development and implementation of technological capabilities so that firms can shape and accomplish their strategic and operational objectives". They also proposed TM activities, processes, supporting tools, and a framework in which these TM activities and tools can interact (Cetindamar, Phaal & Probert 2016):

- **Patent analysis.** Tools used to translate technology patent information into useful metrics for TM decision making
- **Portfolio management.** Management tools used to manage two or more projects grouped according to some criteria
- **Technology Roadmap (TRM).** Graphical chart or tool that is used to map technology projects, expected outcomes and milestones from the current period to a desired state in the future
- **S-Curve.** A tool used to determine or predict the life cycle of a technology, product, or industry
- **Stage-Gate™.** Product management tool for new product development (Cooper 2017). It uses a stage-wise process that consists of decision points (gates), along the process to assess set milestones and track progress.
- **Value analysis.** Tools and techniques used to assess the perceived value of a technology or product in accomplishing its intended objectives relative to alternatives and strategic objectives.

- **Technology Readiness Level.** A tool that is also used to assess the readiness of the technology for commercialisation. This is a scaled based tool, developed by NASA (Mankins 1995), used to evaluate the level of technology development maturity.

These TM tools and techniques have also been proposed to be used in SE processes and activities. For instance, Altunok & Cakmak (2010) developed a TRL calculator and algorithms for the Turkish Defence to validate and verify new technology maturity. Collins & Pincock (2010) also proposed a TRL-based mechanism to evaluate a next-generation nuclear plant's readiness systems, sub-systems, and components. A South African case study was conducted in which TRLs were adapted to assess the maturity of 4IR technologies (Gillwald et al., 2019). This paper seeks to further explore the use and the relationship between TRM in SE and vice versa.

Technology Roadmaps

TRMs are TM tools used in many sectors and industries for TM applications such as planning and forecasting (Phaal et al., 2012). These are graphical charts that map technology projects, technologies, systems and products with business strategies and markets. Moreover, they can be easily formatted or adapted to fit the purpose of the intended application.

A standard TRM is a two-dimensional chart that shows hierarchical layers on the vertical axis and time on the horizontal axis (See Figure 2). The hierarchical layers represent organizational decisions about the markets, business, products and services, technologies, and projects. Therefore, TRMs can be used to align technology projects with technologies, technologies with products and services, products and services with business strategies, and business strategies with the target market(s). Each layer on the chart consists of milestones that can be positioned to address three main questions; *know-how*, *know-what*, and *know-why* questions. The time axis represents the period associated with the milestones in each layer, from the past to some point in the future.

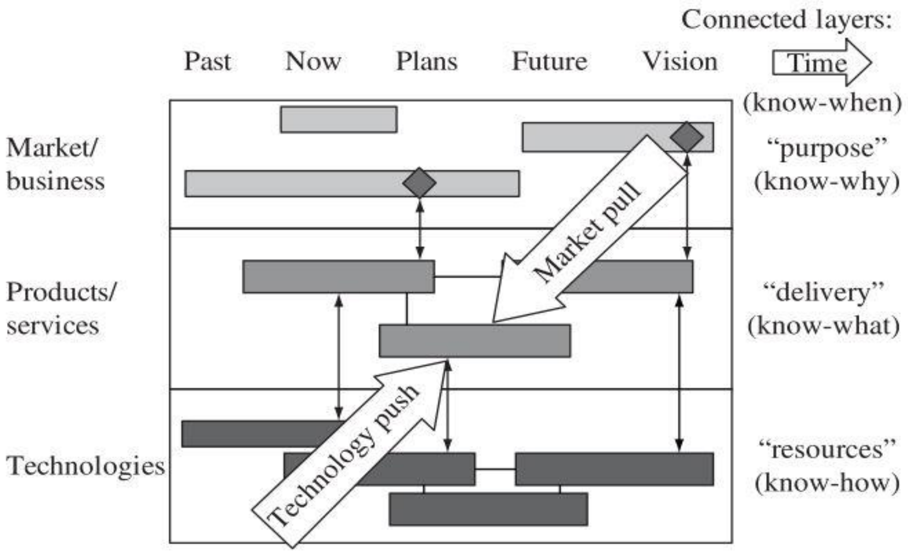

Figure 2: Generic Roadmap structure (Johanna et al. 2008)

Figure 3 depicts an example of an implementation of a generic representation of a roadmap standard form (Johanna et al. 2008). The figure shows each layer's managerial function and the associated objectives ("Respond to column"). In addition, it also shows the mapping between the managerial functions and decision business strategies.

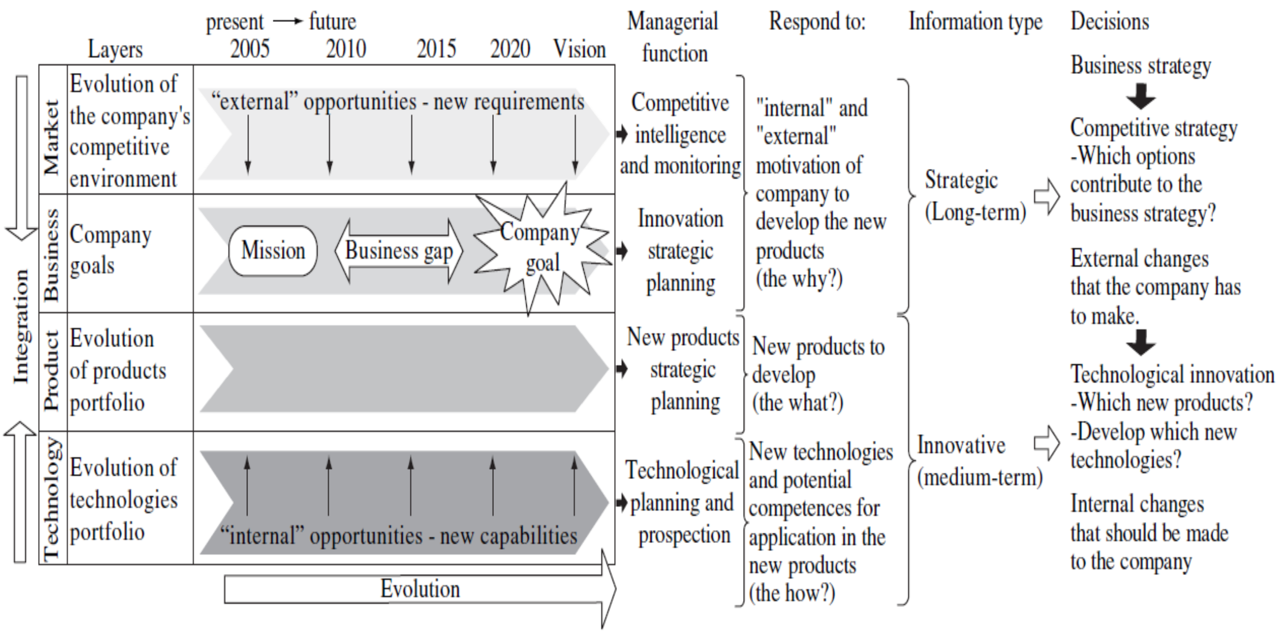

Figure 3: Generic representation of the roadmap and its layers (Johanna et al. 2008)

Roadmapping

TRMs are developed or constructed through a roadmapping process, as shown in Figure 4 (Garcia & Bray 1997). This process consists primarily of three major phases:

- **Preliminary Activity.** This first phase includes activities before the construction of the TRM. It involves identifying the purpose or need for the TRM, success and required conditions, and resources. Moreover, it consists of the buy-in from management leadership and sponsors for the TRM process.

- **Development of the TRM.** This second phase is a multi-stage phase that includes all the activities required to construct the TRM. These activities include identifying the user needs product to satisfy the need, technologies and drivers for the identified products, and associated timelines. The output of this phase is the TRM chart.

- **Follow-Up Activity.** This last phase, sometimes called the “action plan”, includes activities to action the resulted TRM vision. It includes activities such as the validating and updating of the TRM, developing technology projects, and communicating the TRM vision to the various stakeholders.

Although technology roadmaps and roadmapping are helpful tools for technology analysis and planning, constructing a roadmap is a challenge. In addition, roadmapping participants usually base their decisions on experiences and tacit knowledge about the subject matter or the technology. There is also a lack of use of scientific and robust tools in the roadmapping process. Hence, there is a need to develop a scientific, robust, and objective guide for roadmap and roadmapping, including the use of TM methods and support tools.

Various researchers have postulated the alignment of SE practices with other management tools. Smith & Oosthuizen (2012) have developed a model that aligns the SE process with an integrated capability life cycle used in Defence acquisition projects. Peterson & Schindel (2016) argued that SE could be aligned with business strategy decisions by shifting the focus beyond process focus. Specking, Parnell & Pohl (2020) identified areas of collaboration or enhancement between SE and Portfolio Management.

Phase I. Preliminary activity

1. Satisfy essential conditions.
2. Provide leadership/sponsorship.
3. Define the scope and boundaries for the technology roadmap.

Phase II. Development of the Technology Roadmap

1. Identify the "product" that will be the focus of the roadmap.
2. Identify the critical system requirements and their targets.
3. Specify the major technology areas.
4. Specify the technology drivers and their targets.
5. Identify technology alternatives and their time lines.
6. Recommend the technology alternatives that should be pursued.
7. Create the technology roadmap report.

Phase III. Follow-up activity

1. Critique and validate the roadmap.
2. Develop an implementation plan.
3. Review and update.

Figure 4: Three phases in the TRM process (Garcia & Bray 1997)

SE practices have been proposed methods to construct TRM instead of the traditional workshop-based approach, particularly in Model-Based SE (MBSE) (Golkar & Garzaniti 2020; Gradini et al. 2019). This paper seeks to extend this approach by identifying other areas of collaboration or enhancement between SE practices and TRM.

Relationships between Systems Engineering and Technology Roadmapping

As stated herein, this paper seeks to explore the relationship between the three concepts, processes, TRM, SE and ST. It is postulated that the three concepts can collaborate or support one another. Figure 5 shows a model of the relationship, captured in a systemigram. For instance, TRM can act as a tool or a data source for SE processes, and SE can be used as a tool, and to some extent, a data source for the TRM processes. ST enables both TRM and SE to cope with complexity in the technology deployment environment and context. When considering the theory discussed in the preceding sections, it is noted that TRM may benefit from systems-based approaches that investigate the relationships between technologies. This can lead to the emergence of unique and robust, and resilient systems. Also, the relationships between technologies and business processes (value chain) within an organisation may improve the utilisation of technologies.

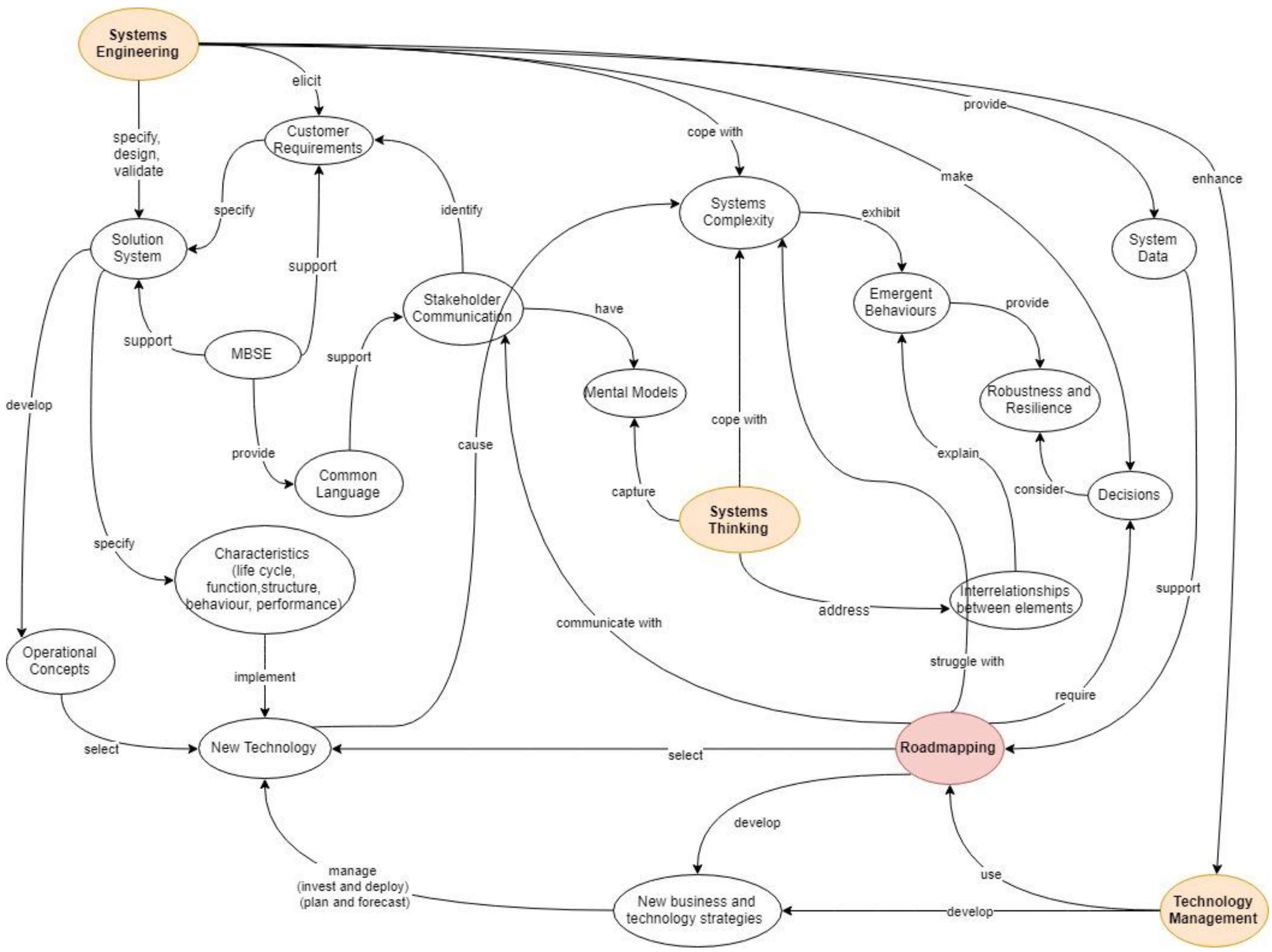

Figure 5: SE and TRM Symbiotic relationship Systemigram

The areas of collaboration and enhancement between the SE and TRM are summarized below:

- The TRM can act as a data source for system decomposition in the SE process. The different layers of the TRM can support the identification of candidate technologies, products, and sub-systems during the conceptual system phase of the SE process. Ensuring that these identified artefacts are in alignment with the overall business strategies.

- The TRM can be used as a tool for decision making. During the trade studies of the SE process, the TRM can be used to select candidate technologies, products, and sub-systems for system development. Ensuring that these identified artefacts are in alignment with the overall business strategies.

- The TRM can act as a bridge to other business processes. TRM can easily integrate with business processes; therefore, it can be used as an anchor point to incorporate the SE processes with business processes.

- The TRM can be used as a tool for systems development planning. The TRM can provide system development timelines planning for the SE process. Also, the SE process requires knowledge of the state of various solution technologies to support the system design and implementation processes, which the TRM process can provide.

- The TRM, sometimes called the “dynamic system framework”, provides a structure within which the evolution of the system of interest can be mapped for the SE process.

- The TRM provides a common language to communicate technology and business strategies to different stakeholders. Also, SE strives to provide a common language to different systems stakeholders. Hence, using various systems views of the SE process, particularly from MBSE, may provide useful visualisations of the system and technology for the TRM.

- The SE process can be used as a data source for the TRM. The hierarchical and recursive nature of the system decomposition activity of SE can provide data for the different layers in the TRM.
- The SE process can identify and refine the evolution of candidate technologies, systems (including enabling systems) and products. The requirements management definition and management activities of the SE process can be used to refine and evolve the TRM candidate elements in the different layers.
- The SE process can be used to cascade strategy elements in the TRM. The requirements management activity can be used to cascade products, systems, and technologies in the TRM.
- The SE process can be used to manage the evolution of the TRM life cycle. The verification and validation process of the SE can be used to ensure that the TRM is a true reflection of the organisation vision on its technologies.

Concluding Remarks

Not only does the inception of advanced technologies give rise to new capabilities, but it also gives birth to new and complex technologies and systems. These new complexities required businesses to develop new strategies and management frameworks to cope and to be competitive. TRMs have been used as tools in TM for strategic planning, while SE practices (processes and activities) have also been used to manage systems complexities.

This study explored the use of SE principles in the TM process, in particular for TRMs and vice versa. SE practices and processes can be used as data sources or tools for the TRM and TRM processes, and the TRM processes can be used as data sources and tools for the SE practices and process.

The study outputs identified the need for technology managers to augment their knowledge of TM through the understanding of the SE practices to develop robust, sound, and achievable technology and business strategies. However, the two processes would not be able to leverage from each other without the support of management. Management, in particular middle and top management, is required for the effective exploitation of the two processes in the organization.

This study considered the relationship between SE and the TRM. However, TRM is a subset of TM, which involves several processes, activities, and tools (Cetindamar, Phaal & Probert 2016). Therefore, future studies should consider extending the scope of the relationship to the other aspects of the TM discipline. Moreover, future studies should consider a research methodology where experiences of both the TM and SE practitioners can be factored into the relationship model.

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Biographies

Linda Malinga is a Senior Engineering Specialist at the Council for Scientific and Industrial Research (CSIR), focusing on Integrated Capability Management in the Command and Control Information System research group. A researcher who has published papers and book chapters in various fields including modeling and simulation; crowd control modeling; next generation networks; and ICTs in society. He holds a BSc. degree in Electrical and Information Engineering from the University of the Witwatersrand (2005, South Africa); an honours degree in Electronic Engineering and a MEng degree in Technology and Innovation Management from the University of Pretoria (2016 and 2020, South Africa). His current research interest is on Emerging Technologies and Innovation Management in the techno-disruptive world.

Rudolph Oosthuizen joined South African Air Force in 1990, where he performed systems engineering roles in electronic warfare and Command and Control (C2). At the University of Pretoria, he obtained a B.Eng (Elec 1994), B.Eng (Hons) (Indus 1998), MEM (2002) and PhD in Engineering Management in 2015. In 2008 Rudolph joined the CSIR as a Systems Engineer on multiple C2 projects. Since May 2020, he has been appointed as a senior lecturer at the Graduate School of Technology Management at the University of Pretoria, where he teaches Systems Engineering and Systems Thinking. Lately, his focus is on Data Science and Artificial Intelligence for decision support and situation awareness. Rudolph is registered as a Professional Engineer with ECSA and a Certified Systems Engineering Professional (CSEP) with INCOSE.