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RESEARCH ARTICLE

A Model-Based Systems Engineering Framework for Technology Roadmaps (MBSE-TRM): Application to Electronic Warfare Systems

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ABSTRACT Technology-intensive industries face accelerating change driven by disruptive innovations, geopolitical shifts, and the dynamics of Industry 4.0. In this environment, managers require strategic tools that can align markets, products, and technologies over time while retaining adaptability. Technology roadmaps (TRMs) are widely used for this purpose; however, current practice remains largely qualitative, workshop-led, and reliant on subject matter expertise. This constrains their utility in dynamic environments. This paper develops a Model-Based Systems Engineering framework for Technology Roadmaps (MBSE-TRM) to address these limitations. The research advances theory by introducing a conceptual metamodel that captures the ontology of TRM, formalizing its structure and lifecycle using SysML, and demonstrating how tacit practitioner logic can be represented explicitly. Validation is undertaken in the domain of Electronic Warfare (EW) against radar, a technology-intensive field characterized by rapid innovation cycles and strategic importance. The findings show that MBSE-TRM enables improved transparency, traceability, and adaptability, supporting managers and engineers in steering innovation strategies under conditions of volatility. By bridging systems engineering principles with technology strategy, MBSE-TRM provides a structured yet flexible framework for aligning strategic intent with evolving technology options in Industry 4.0 and beyond.

INDEX TERMS Model-based systems engineering, electronic warfare, technology road mapping, innovation strategy, technology management.

I. INTRODUCTION

The origins of strategy date back several thousand years to military conflict, with one of the earliest known works, "The Art of War" from ancient China addressing the definition of strategy and tactics [1]. The formal study of business strategy and practice emerged in the 1960s to guide competitive advantage [2]. Technology roadmapping emerged from industry practitioners in engineering management in the 1960s seeking to align R&D projects to technical performance and business objectives [3].

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Technology roadmaps (TRM) are described as "a powerful yet intuitive structured-visual technique that supports strategic and long-range planning allowing for connections between developing markets, products, and technologies as they progress through time" [4], [5].

While TRMs are widely used, their current practice remains predominantly qualitative and workshop-led [6]. This flexibility aids sense-making but often results in limited consistency, traceability, and reuse. Recent advances in technology roadmapping include scenario-based roadmapping, digital roadmapping, and semi-automated TRM generation, which collectively represent a trajectory toward more dynamic, data-informed, and continuously updated TRM approaches [7], [8], [9], [10], [11], [12], [13]. An emerging area of research is the application of model-based TRM (MB-TRM) [14], [15]. However, there remains a research gap in the development and formalization of ontology of TRM and the TRM lifecycle from cradle to grave.

This challenge mirrors the evolution in systems engineering (SE), which transitioned from document-based to model-based approaches (MBSE) [16]. Drawing from this analogy, this research adopts a systems-view of TRM to develop a Model-Based Systems Engineering framework for Technology Roadmaps (MBSE-TRM). The paper contributes by: (1) developing a conceptual metamodel to capture the ontology of TRM; (2) formalizing TRMs and the TRM process using Systems Modelling Language (SysML); and (3) validating the framework in the technology-intensive domain of Electronic Warfare (EW) against radar. Theoretically, MBSE-TRM advances the formalization of TRM by providing an explicit metamodel and executable representation, while it equips managers with a model-based toolset to maintain coherence between strategic intent and evolving technology options; capabilities increasingly critical in Industry 4.0 and beyond.

The remainder of this paper is structured as follows. Section II reviews TRM practice and prior formalization attempts. Section III outlines the research methodology. Section IV develops the MBSE-TRM framework. Section V applies the framework to EW as a validation case. Section VI discusses implications, limitations, and future research.

II. LITERATURE REVIEW

A. THEORETICAL BACKGROUND

The origins of technology road mapping were explored in [3] and is said to trace back to engineering management in the 1960s conducted in organizations such as ''NASA, Boeing, GE, Lockheed, USAF, Rockwell International and the US Department of Energy'' and subsequently more recent seminal contributions by the high-tech organizations of ''Motorola, BP, Philips, EIRMA, Lucent Technologies and the Semiconductor Industry Association''. TRMs balance product, business, and market perspectives, hence terms like strategy or product roadmaps are sometimes used [5]. Roadmaps may take various forms and have a wide diversity of graphical representations and levels of detail [5]. The most widely used format is the multi-layered roadmap comprised of several layers typically for technology, product, and market, each evolving with time capturing both market pull and technology push effects. The time dimension may be linear or non-linear depending on purpose [4].

The first formal TRM publication was Motorola's 1987 approach defining technology broadly as ''the application of science to solve development capability problems'' [17]. The semiconductor sector in the United States was the first sector-level application of TRM in 1991 by the US National Advisory Committee on Semiconductors, leading to the publication of the International Technology Roadmap for Semiconductors (ITRS) in 1999 [18]. The examples above demonstrate the vast range of diagrammatic representations reflecting no set of agreed-upon conventions on roadmap visualizations as validated in [19] with a collection of 450 roadmap visualizations.

The TRM process, referred to also as roadmapping, is the methodology used to formulate a TRM [20]. The TRM process is required to solicit and abstract complex information into an intuitive strategy that is readily understandable [6]. The T-Plan, S-Plan, and Operations and Technology Roadmap (OTR) are formalized TRM processes based on process-driven workshops adopting a ''fast-start'' rapid prototyping philosophy [21], [22], [23]. The analytical TRM technology development envelope (TDE) method, combines Delphi-based expert elicitation with the analytical hierarchy process (AHP) to assess emerging technologies [24], [25]. In the field of technology foresight and futures thinking, scenarios are narratives on potential futures leading to scenario-based TRMs [26], [27]. Hybrid TRM processes have been demonstrated in [28] and [29] that augment qualitative workshop-based methods with quantitative data such as bibliometrics and patentometrics. Despite their value, current TRM practices remain workshop-based and reliant on subject matter expertise. These limitations highlight the need for formalization.

B. RELATED WORK ON TRM FORMALIZATION

TRMs are semi-structured by nature, balancing abstraction and detail, which has led researchers to pursue formalization to capture their underlying logic more systematically [30]. Recent advances include agile TRMs for technology foresight [7], integrated innovation roadmaps [8], portfolio-oriented TRMs [9], and design science-based methods for IP portfolios [10]. The COVID-19 pandemic also drove digital and distributed roadmapping practices [11], [12], while semi-automated tools such as NERMAP apply natural language processing to generate preliminary TRMs [13]. These efforts show a trajectory toward greater structure, yet remain partial steps rather than a fully formalized, model-based approach.

An emerging area of research is MB-TRM which aims to augment qualitative expert insights with structured models. The feasibility of MB-TRM was demonstrated in [14] using document-based NASA roadmaps. A generalized metamodel of TRM's informational structure was developed in [15], and validating reconstructing roadmaps. A model-based roadmapping architecture, primarily oriented towards organizational decision support, was shown in [31]. In [32], a concurrent design approach to build MB-TRM demonstrated the usage of models for evaluating potential product architectures against figures of merit and several time intervals.

A metamodel to support MB-TRM was developed in [15]. The application-independent metamodel was developed and validated by generalizing and formalizing existing

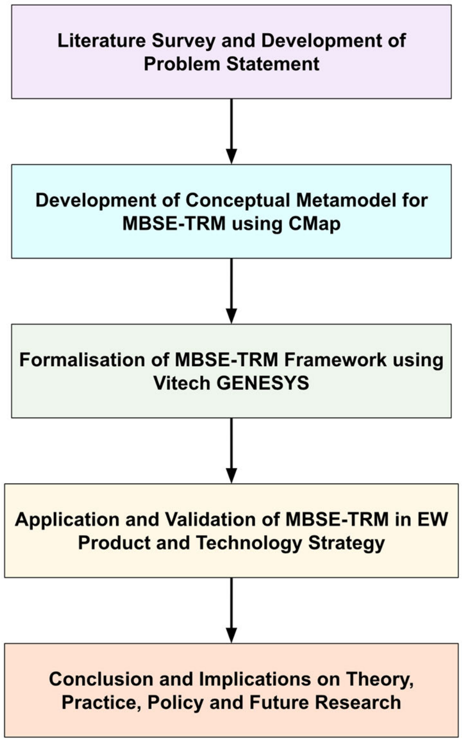

FIGURE 1. Research methodology.

document-based roadmaps. The MB-TRM was further applied to a smart autonomous vehicle cockpit design [33] and domain specific languages and syntax developed in [34] and [35]. A concurrent roadmapping methodology that allows for updating of a TRM based on a model-based design was shown in [36].

Whereas [14] established feasibility, [15] generalized an informational structure and [31] decision support, this paper advances MB-TRM by formalizing TRM ontology and lifecycle in SysML and validating the framework in the technology-intensive domain.

While the literature review has focused on technology roadmapping and MBSE as domain-independent foundations, EW is used in this work as a demanding validation case. Relevant EW and radar literature is therefore discussed in detail in Section V, where the proposed MBSE-TRM framework is applied and evaluated within an operationally realistic context.

C. RESEARCH GAP AND OBJECTIVES

An analogy may be drawn with SE, which transitioned from document-based to MBSE, employing modeling principles, methods, languages, and tools in the SE process [16]. TRMs, however, have not undergone a similar transition. The research gap is:

- Lack of Formalization in TRM Methodologies: Traditional TRMs rely on informal, document-based tools and practitioner judgment, resulting in limited consistency, traceability, and reuse.
- Limited Application of MBSE in Roadmapping: While MBSE is widely applied in systems development, its use in TRM remains sparse, with few formal models or system representations.
- Absence of Lifecycle Dynamics in Existing TRMs: TRMs are often static artefacts rather than dynamic systems that evolve with feedback and changing contexts.
- Lack of a Reusable and Unified TRM Metamodel: Few frameworks provide a reusable structure with standardized semantics and syntax for roadmap design, analysis, and communication.

This research develops MBSE-TRM, which formalizes TRMs as a structured, systems-oriented framework. Its metamodel, captured in a concept map, defines interconnected layers (trends, capabilities, products, technologies, research, resources) supported by synthesized strategic inputs. The conceptual model is formalized in SysML to represent structure, behavior, and lifecycle. EW, with rapid innovation cycles, is used as a demanding validation case.

Adaptive and learning-enabled system behavior, including that arising from AI/ML-based technologies, is addressed within the proposed MBSE-TRM framework at an abstract level. Rather than modeling algorithmic implementations directly, learning loops, adaptation criteria, and decision logic are represented through lifecycle feedback mechanisms, update triggers, and state transitions. This approach enables the roadmap to accommodate emergent and evolving system behavior while preserving reusability, standardized semantics, and abstraction from implementation-specific technologies.

III. RESEARCH METHODOLOGY

From the literature survey, a research gap was identified in the development of formalized MB-TRM for technology-intensive product development such as in EW. The research methodology is summarized in Fig. 1. This study is grounded in the proposition that although TRMs are often built using informal methods and expert judgment, they reflect a deeper, structured logic that can be systematically uncovered. By taking a systems view of the roadmap and its lifecycle process, this research seeks to formalize the ontology of TRMs by defining the key concepts, relationships, and rules governing the TRM lifecycle from initial construction through evaluation and refinement.

The methodology adopts a metamodeling approach: a conceptual metamodel is first captured using concept maps and then formalized in SysML to enable traceability, coherence, and lifecycle reasoning. The MBSE-TRM framework thus translates tacit expert logic into an explicit, executable model. Methodologically, the research draws from engineering systems thinking and design science. The central artefact, the MBSE-TRM metamodel, addresses a practical problem while contributing to formal knowledge. The research is both explanatory (uncovering latent roadmap structure) and prescriptive (providing a repeatable modelling approach for roadmap development, evaluation, and use).

Philosophically, the study adopts a positivist-pragmatist stance, combining hypothesis testing and objective analysis with a pragmatic focus on utility and methodological flexibility. It acknowledges that roadmap structures emerge from practitioner context and accumulated experience and seeks to capture this constructed logic in a formal, reusable way through a design science methodology. This allows for a balance of formal rigor with domain relevance, creating a foundation for future work on model-based innovation strategy and lifecycle technology planning.

IV. FRAMEWORK DEVELOPMENT

A. CONCEPTUAL FOUNDATIONS AND METAMODEL DEVELOPMENT

The development of the MBSE-TRM framework begins with a simple yet powerful proposition: that despite their many forms including diagrams, templates and processes; TRMs share an underlying ontology that gives them coherence, utility, and enduring value. In this research, ontology refers to the foundational structure of TRMs: the set of concepts, relationships, and rules that, while often implicit, make roadmaps useful across contexts.

This ontology can be systematically uncovered and formalized by taking a systems view. In doing so, this research seeks to surface the foundational structure i.e. the ''truth'' beneath the practice that makes TRMs an effective strategic tool. Practitioners may not articulate this logic explicitly, but their decisions and roadmap structures often reflect patterns shaped by accumulated experience, strategic considerations, and the informal replication of existing roadmap formats. By taking a systems view of the roadmap and its lifecycle process, this research seeks to uncover and formalize the underlying ontology of TRMs to define the key concepts, relationships, and rules governing the TRM life cycle from initial construction to ongoing evaluation and refinement.

The study adopts a metamodeling approach to identify and represent this ontology. A metamodel is a ''model of models'' that defines the structure, semantics, and relationships governing a modelling framework. In this research, the metamodel captures the underlying logic of TRMs and the TRM process (rather than any specific TRM instance) as a necessary precursor to formalization. Accordingly, this research constructs a conceptual metamodel that describes TRMs and the TRM process as a preceding step to formalization thereof. Concept maps, which are structured diagrams used to represent organized knowledge, are employed as the primary technique for developing the conceptual metamodel. The concept map for MBSE-TRM is shown in Fig. 2. For readability, a simplified version of the concept map highlighting the primary MBSE-TRM layers is provided in the supplementary material.

The concept map was created in CmapTools. The concept map is a step that precedes the definition of a formal metamodel to help explore key entities, relationships, and constraints in an intuitive way. Metamodels are often built from domain knowledge with the use of the concept map to help structure that knowledge before translating it into a formal model. One may think of a concept map as an intermediate artefact that serves as a bridge between informal knowledge representation with formal modelling. The concept map is also excellent for brainstorming and early structuring of a metamodel.

The creation of the concept map was based on the author's domain knowledge, experience and inductive reasoning from existing roadmap formats. Several roadmaps were examined including drawing from the most widely used format which is the multi-layered roadmap comprised of several layers typically for technology, product, and market, each evolving with time. The concept map also aids with the identification of hierarchical relationships, such as generalization, composition, or dependencies superimposed with the general TRM ''Why-What-How-When'' concepts [37], [38]. In MBSE-TRM, the concept map illustrates how technology, roadmaps, decision-making, and resources interconnect before defining the metamodel structure in SysML. By mapping out relationships visually, concept maps help validate assumptions before committing to a formalized metamodel.

The concept map is a visual tool to deconstruct the concepts, organize knowledge, solidify understanding and build a deep understanding of the metamodel. While the concept map is presented as a finished research output, the development of the concept map followed an iterative approach during this research. The concept map is organized with a main concept in the middle followed by multiple levels of decomposition of the main concept each adjoined by linking words. The linking words form a ''proposition'' which are two concepts joined by linking lines to depict the dependency that one concept influences or results in another. ''Cross-links'' are linking lines that show relationships between different regions of the concept map. In both ''propositions'' and ''cross-links'', linking words typically consist of one to two words used to describe the dependency. In this concept map, it should be noted that in all cases of a ''proposition'' and a ''cross-link'', the dependency is only shown in one direction, but a reciprocal dependency exists. For example, ''Products comprise of Technologies'' is shown on the concept map but a reciprocal proposition exists that ''Technologies form part of Products'' is true but not shown. This was an intentional decision in the construction of the concept map to balance clarity versus verbosity. Selection of the most suitable linking words for the concept map is crucial for clarity and precision. Linking words can cover a wide range of dependencies such as causal, structural, functional, process, comparative, requirement, and ownership relationships. Another important principle used is that each concept only appears once. Colorization was used in the concept map to group themes together which in this case are related to different layers in the multi-layer TRM.

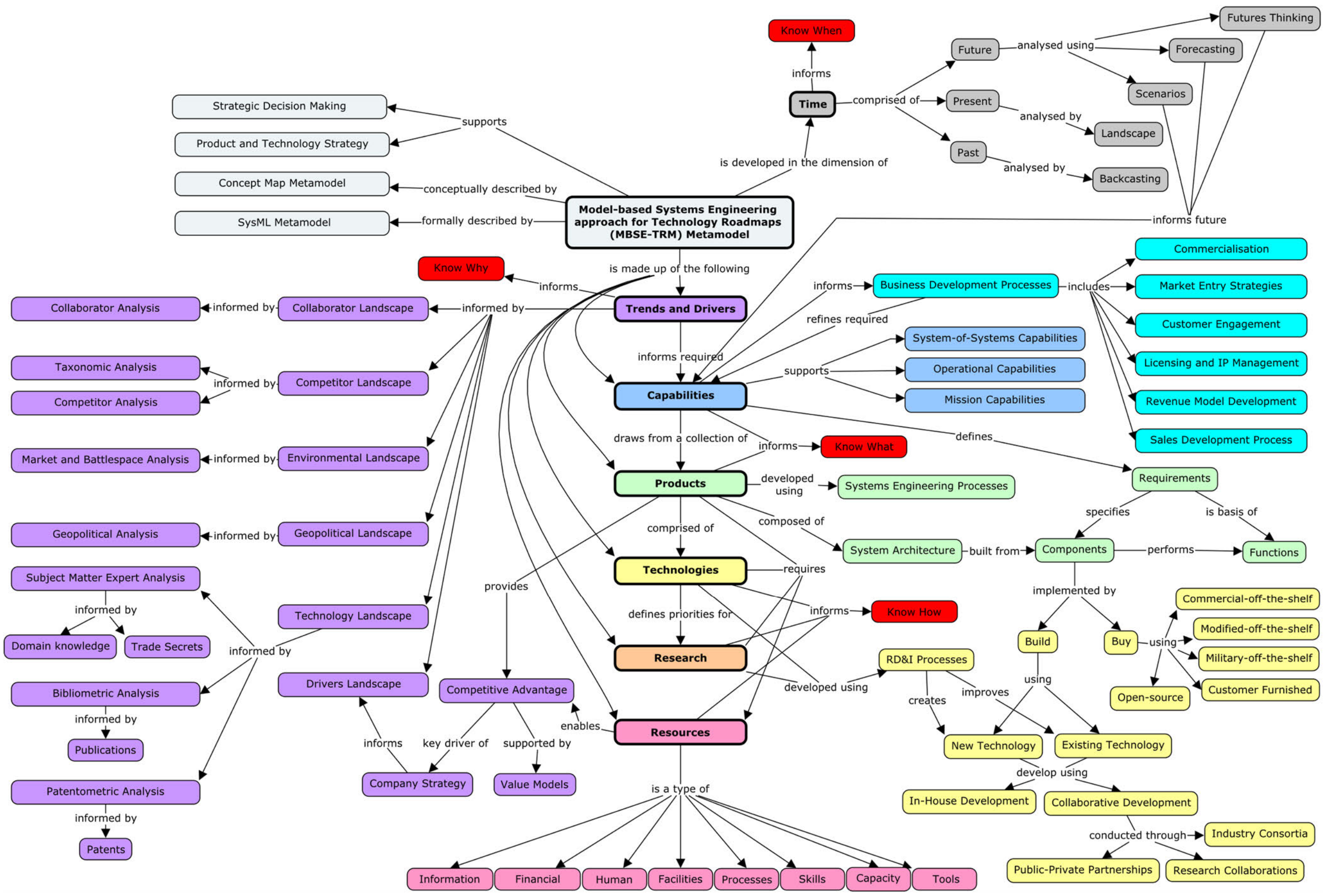

FIGURE 2. Concept Map for MBSE-TRM.

Having explained the premise and principles used, the semantics (what each concept means and how it fits within the system) and interrelationship for the MBSE-TRM metamodel are detailed. The MBSE-TRM metamodel starts with the main concept depicted by the node "Model-based Systems Engineering framework for Technology Roadmaps (MBSE-TRM) Metamodel". The MBSE-TRM is noted to support strategic decision making, product and technology strategy in the concept map.

Nodes are created to represent each of the MBSE-TRM layers as follows; "Trends and Drivers", "Capabilities", "Products", "Technologies", "Research", and "Resources". The "Resources" are of several types including "Information", "Financial", "Human", "Facilities", "Processes", "Skills", "Capacity", and "Tools". Furthermore, dependencies which represent the semantic relationships with emphasis on structural relationships between these layers are captured such as "Trends and Drivers" inform required "Capabilities", "Capabilities" draw from a collection of "Products", and so on as detailed in the concept map.

The semantic relationships above cover the basic structural representation of the TRM. The temporal nature of a TRM is a crucial consideration and requires special consideration in modelling. TRMs are developed in the dimension of time and must consider the past, the present and the future. Techniques typically employed in the analysis of the temporal dimension of the TRM include but are not limited to backcasting, landscaping, scenarios, forecasting and futures thinking. The inclusion of the temporal consideration generalizes the TRM to include scenario based TRMs.

Next, having defined the TRM structural and temporal aspects, the metamodel is extended to include considerations of dependencies at each node or layer of the TRM. The "Trends and Drivers" layer is informed by several landscapes including, "Collaborator", "Competitor", "Environmental", "Geopolitical", "Technology", and "Drivers" landscapes informed by supporting analyses. While this list is comprehensive, there are likely several further landscapes that can be used such as market landscape, and policy landscape. Therefore, this list should not be seen to be exhaustive.

The premise of the "Capability" layer introduced in [30] denotes several concepts with the most basic being that a product offers a user some operational capability. Furthermore, system-of-systems capabilities include the paradigm that organizations can combine several products to offer composite offerings. Typical architypes could include selling a hardware device and complementary software services. Lastly, mission capabilities refer to a military context which could for example include combining multiple products to achieve the ability to suppress enemy air defenses during a strike mission by deploying stand-off jamming and anti-radiation missiles.

The ''Capabilities'' also informs ''Business Development Processes'' and the reciprocal of '''''Business Development Processes'' refines the required ''Capabilities''. ''Business Development Processes'' includes but not limited to ''Commercialization'', ''Market Entry Strategies'', ''Customer Engagement'', ''License and IP Management'', ''Revenue Model Development'', and ''Sales Development Process''. ''Products'' are developed using ''Systems Engineering Processes'' comprised of system architectures built from components performing the required functions. To differentiate two concepts that can be conflated, SE principles are used in the formulation of the MBSE-TRM and distinctly, SE principles are used in the design of products which is a node in the MBSE-TRM.

B. FORMALIZATION OF THE MBSE-TRM FRAMEWORK USING SYSML

Building on the conceptual metamodel developed in the previous section, this section formalizes the MBSE-TRM framework using SysML. As explained in [39], ''all languages have a set of symbols or signs, known as semantics, that are used like we use letters and numbers to form expressions. Similarly, every language has a syntax that defines proper ways of combining the symbols to form thoughts and concepts''. In the context of modelling, these two elements, semantics (meaning) and syntax (structure and form) are brought together through a schema, which defines valid concepts, relationships, and rules. SysML enables this integration by offering both a standardized syntax and the ability to define domain-specific semantics through structured schemas or metamodels.

SysML is a widely adopted modelling language in MBSE used to specify, analyze, design, and verify complex systems. It supports the representation of both structural and behavioral aspects of a system, making it well-suited to formalize the multi-layered logic of the MBSE-TRM framework. The goal of this formalization is to translate the conceptual structure and semantics of the TRM metamodel into a precise, executable, and traceable model. This enables lifecycle consistency, system-level reasoning, and repeatable application across diverse technological domains.

In this research, Vitech GENESYS is used as the MBSE tool. GENESYS is built upon the Systems Definition Language (SDL), which aligns with the SysML standard and adds benefits such as semantic precision and natural language interpretability [40]. While SysML provides a standardized modelling syntax, SDL enables semantic integration and model execution within a cohesive environment, ensuring consistency across structure, behavior, and requirements. Several SysML-compliant MBSE tools are available and widely used in practice, including Cameo Systems Modeler, Sparx Systems Enterprise Architect, and IBM Rhapsody, which provide robust support for SysML diagramming, requirements traceability, and system architecture modeling. In this research, Vitech GENESYS was selected as the primary MBSE tool due to its strong emphasis on a central semantic data model, executable behavior modeling, and SDL, which enables tighter integration between structure, behavior, and lifecycle logic. These capabilities were particularly well-suited to the objective of formalizing the ontology and lifecycle of technology roadmaps as an executable, model-centric framework. Importantly, the MBSE-TRM framework itself is tool-agnostic and can be implemented in other SysML-compliant environments, subject to equivalent support for metamodeling and behavioral execution.

The SysML model of the MBSE-TRM framework is constructed using Physical Block Diagrams, Hierarchy Diagrams and Block Definition Diagrams (BDDs) to represent structure and Activity Diagrams and Enhanced Functional Flow Block Diagrams (eFFBDs) to capture behavior and process flow. Together, these views form a cohesive representation of the TRM as a dynamic system, enabling enhanced traceability, analysis, and alignment with MBSE practices.

The MBSE-TRM metamodel defined in GENESYS constitutes the underlying semantic model, from which all diagrams are dynamically generated. These views are not independent representations, but rather different lenses through which the semantic model is interpreted and interacted with. The metamodel thus serves as a central source of truth that ensures consistency across all visualizations. In this context, the term normative model refers to the MBSE-TRM metamodel as a structured and guiding representation of how individuals or organizations could structure, manage, and analyze technology roadmaps. It reflects an idealized, systemically informed approach to TRM construction, designed to guide strategic decision-making.

Similar to the construction of the concept map, the formalized metamodel shown in this research as a finished work product followed an iterative approach during this research. The MBSE-TRM metamodel exists within a wider enterprise system where technology roadmapping interacts with several organizational processes. As illustrated in Fig. 3, TRM activities are influenced by and provide feedback to domains such as Technology Management, Capability Management, Product Lifecycle Management, Business Development, Systems Engineering Management, Information Management, Intellectual Property Management, Quality Management, Project Management, Financial Management, Human Resource Management, amongst others.

This enterprise-level system of systems context reflects the reality that roadmapping does not occur in isolation but is part of a complex socio-technical system. The MBSE-TRM framework therefore defines the structure and relationships governing the roadmapping process while recognizing its dependencies on external enterprise processes. These interactions ensure that the framework remains extensible and integrable, while the detailed modelling of the surrounding

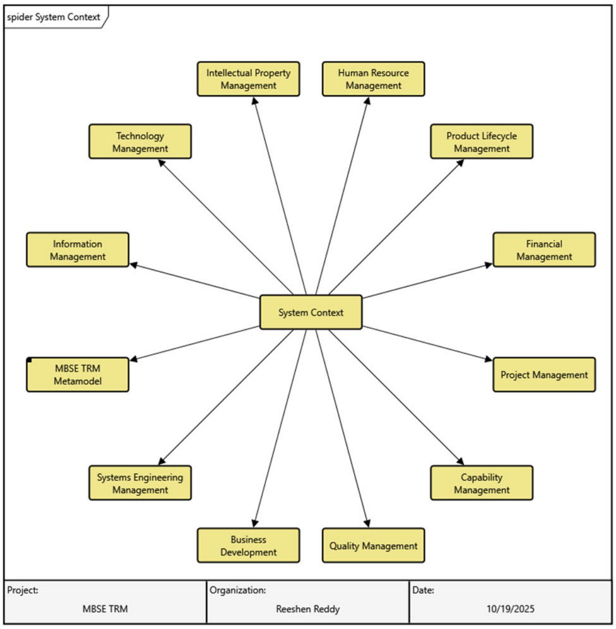

FIGURE 3. Context diagram for MBSE-TRM metamodel.

enterprise functions is intentionally excluded from scope to maintain research focus.

The concept map was parsed to separate structural, behavioral and process flow (or control) aspects. The structure or physical architecture of the MBSE-TRM metamodel is captured in a Physical Block Diagram shown in Fig. 4. Expanded Hierarchy Diagram and BDD are provided as supplementary material. These diagrams present the same underlying semantic model from different perspectives, namely, physical organization, logical hierarchy, and formal structure, respectively. The Physical Block Diagram represents the top-level structural view of the metamodel and captures each layer of the TRM, which was captured as a node in the concept map, as a structural elements or components. Interfaces or associations between elements represented by links carry items between TRM elements. Colorization was used to align to the concept map and group themes together which in this case are related to different layers in the multilayer TRM.

Beyond the hierarchical decomposition, the structural representation of the MBSE-TRM metamodel reflects several important MBSE principles. The framework is organized across multiple levels of abstraction, from the overarching metamodel to distinct roadmap layers and their constituent sub-elements. Each element within this hierarchy serves as a semantic placeholder for synthesizing information during roadmap development. For example, the "Resources" element aggregates diverse enablers such as human capital, infrastructure, and tools needed to realize roadmap outcomes.

The use of composition relationships in the BDD enforces encapsulation and ownership semantics which are represented by the filled diamond annotation in SysML. The physical hierarchy also aligns with the logical ordering of TRM structure. The choice of this cascading structure supports traceability and modularity. Importantly, the MBSE-TRM structure is not static and supports dynamic evolution over time. This adaptability is explicitly captured in the behavioral diagrams that follow, which model the execution and maintenance of the TRM across its lifecycle. These characteristics are essential for a technology roadmap that must adapt to fast-changing contexts such as EW. Collectively, the physical block diagram, hierarchy diagram, and BDD represent a cohesive and semantically rich structure that underpins the dynamic behavioral views introduced in subsequent sections.

While the structural model defines the foundational elements of the MBSE-TRM framework, the behavioral view captures how these elements are operationalized across the technology roadmap lifecycle i.e. the logical architecture. The top-level behavioral or functional view begins with the MBSE-TRM lifecycle that models the processes of roadmap creation, execution, monitoring, and iterative refinement. To model this behavior, the MBSE-TRM lifecycle (and subsequent behavioral views) are formalized using two complementary SysML-aligned representations eFFBD and Activity Diagram, both developed in Vitech GENESYS. The eFFBD diagrams are included in the body of the paper and complementary activity diagrams provided as supplementary material.

The eFFBD and activity diagram collectively highlight the functional flow, control flow, data interactions, and concurrency between roadmap processes, enabling a clear representation of logical sequencing and iteration. Together, these diagrams provide a robust and semantically consistent depiction of system behavior and how the roadmap evolves over time. The MBSE-TRM Metamodel Lifecycle eFFBD is shown in Fig. 5.

In an eFFBD, the flow of control proceeds from left to right. Further, in the eFFBD in Fig. 5 and those that follow, rectangular yellow nodes denote functions, while circular yellow nodes represent control constructs. Each function is labelled with its number in the top row, function name in the middle row, and allocation to a structural element in the bottom row. Rounded grey rectangles indicate data stores or inputs and outputs. Rounded green rectangles represent triggers, which control the execution of functions and are shown entering the function with a double-headed arrow. Similar to structural elements, functions can also be decomposed. Composite functions that are detailed in separate diagrams are marked with a black square in the upper-left corner.

The TRM lifecycle begins with a decision to create a TRM, triggering the "Create TRM" function. In the MBSE-TRM model, this decision is considered external and modelled as an external trigger as it originates from, for example, executive leadership, sponsors, external stakeholders. In the real world, such a decision could include but not limited to, the initiation of a new program or capability development effort, external

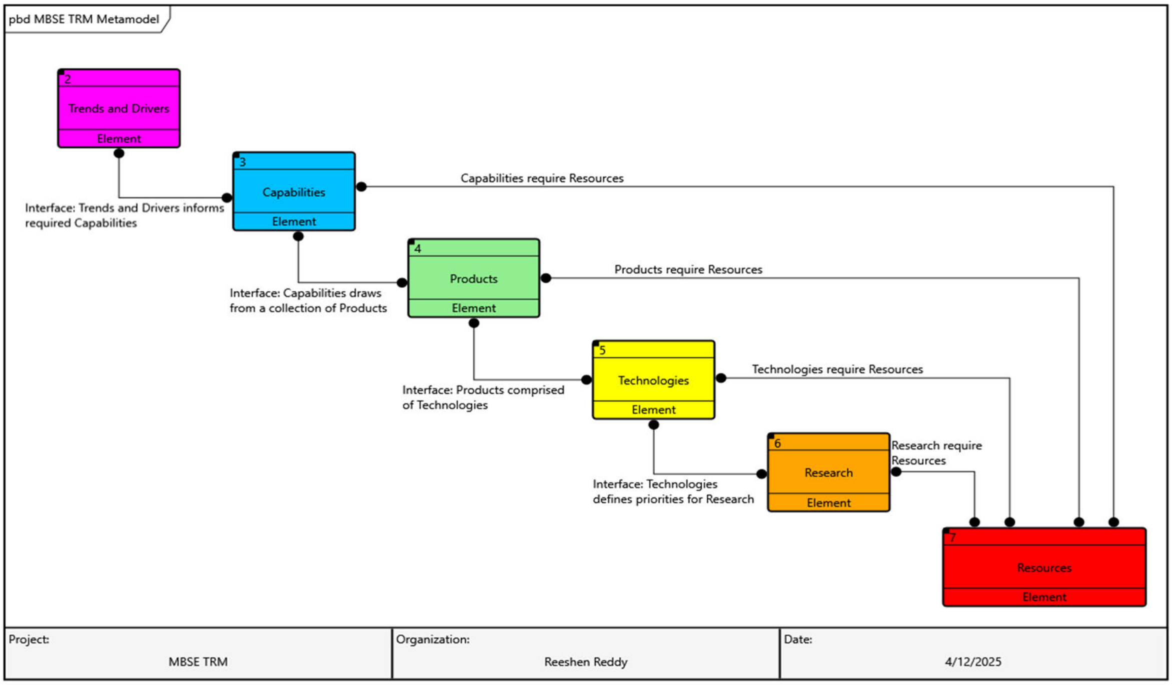

FIGURE 4. Physical block diagram for MBSE-TRM metamodel.

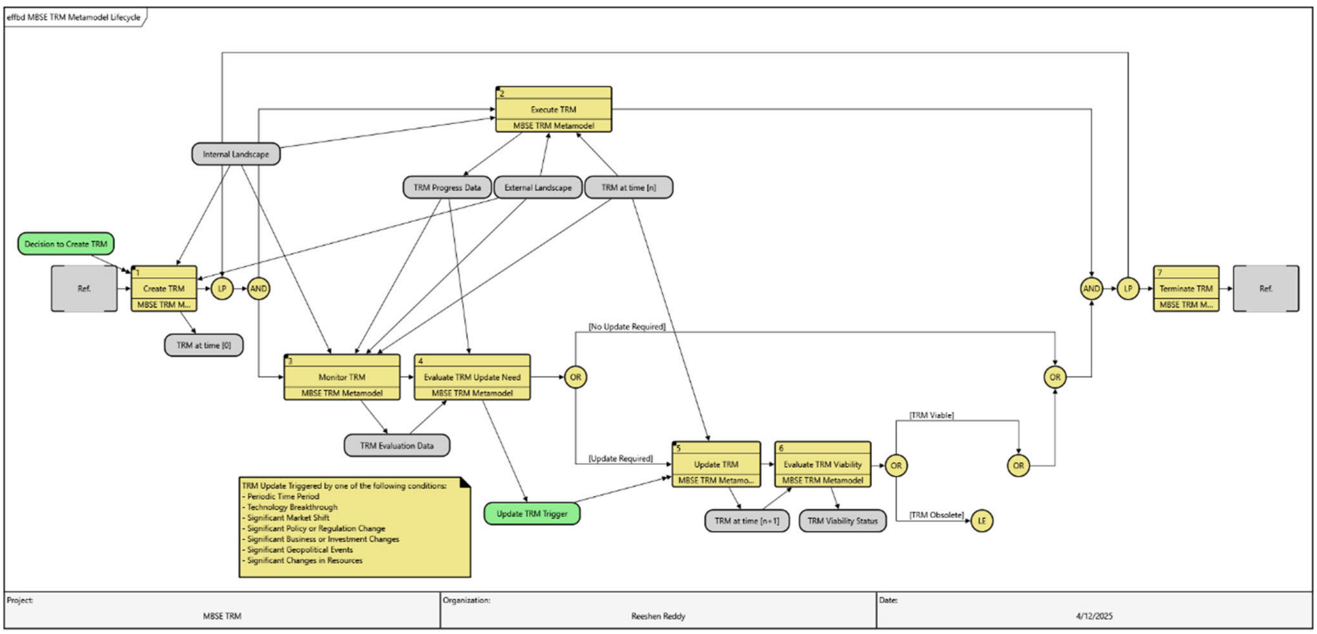

FIGURE 5. eFFBD for MBSE-TRM metamodel lifecycle.

funding opportunities, policy or regulatory shifts, or the identification of disruptive technologies that necessitate long-term technology planning. Additional drivers may include defense modernization directives, alignment with national or sectoral research development and innovation (RD&I) roadmaps, competitive pressures from international peers, the introduction of new mission requirements, or obsolescence risks in critical systems.

Thereafter, the ‘‘Create TRM’’ function results in a ‘‘TRM at time [0]’’ followed by two concurrent branches ‘‘Execute TRM’’ and ‘‘Monitor TRM’’ in a loop. This loop models an important temporal aspect of the TRM with the loop counter represented as ‘‘n’’ in the model. In the ‘‘Monitor TRM’’ branch, there is a decision point that triggers ‘‘Update TRM’’. Several of these functions are decomposed further and will be expanded upon.

The "Update TRM" function is triggered by one of the following conditions: "Periodic Time Period", "Technology Breakthrough", "Significant Market Shift", "Significant Policy or Regulation Change", "Significant Business or Investment Changes", "Significant Geopolitical Events", and "Significant Changes in Resources". The triggering of the TRM provisions for regular periodic updates in which the periodicity of the updates is context and organizational specific modelling a continuous innovation cycle. Further, disruptive innovation events such as technology breakthroughs can trigger an update as well as significant changes to various events. Within the MBSE-TRM lifecycle model, the external trigger represents a formal modeled element that initiates evaluation or update activities within the roadmap. The specific conditions listed in the lifecycle diagram, such as technology breakthroughs, regulatory changes, or geopolitical events, are intended solely as illustrative real-world motivations and should not be interpreted as fixed or exhaustive semantic elements of the metamodel. This separation ensures a clear distinction between model semantics and example instantiations. The set of update triggers illustrated in the lifecycle model is not intended to be exhaustive, but rather representative of typical classes of events that may necessitate roadmap revision. In practice, additional triggers may arise in rapidly evolving technological domains, including supply chain disruptions, breakthrough patents, or other unforeseen external shocks.

The "Update TRM" results in a "TRM at time [n+1]" while the "Execute TRM" uses "TRM at time [n]" modelling the real-world dynamics that a TRM is being executed during the process of updates. This concurrency captures the overlap between ongoing implementation and iterative strategic refinement, a necessary feature in dynamic innovative environments.

Within the update loop, the "Evaluate TRM Viability" function serves as a decision point to determine whether the roadmap remains viable or should be discontinued. If discontinuation is warranted, the loop exits and triggers the "Terminate TRM" function, formally ending the roadmap lifecycle. Such an event could be triggered by reallocation of resources toward higher-priority initiatives, failure to deliver expected outcomes, significant shifts in organizational priorities, structural changes affecting the responsible unit, or the loss of funding required to sustain execution.

Next, we step down a level further to the decomposed eFFBD for "Create TRM", "Execute TRM", and "Update TRM" shown in Fig. 6, Fig. 7, and Fig. 8 respectively. Once a decision has been made to create a TRM or update a TRM, both functions follow a similar functional flow of a collection phase where relevant inputs are gathered from across the strategic, technological, and operational landscape; followed by a synthesis phase, where these inputs are synthesized into structured roadmap layers. This distinction emphasizes the transition from data gathering to value-added interpretation and structuring within the MBSE-TRM framework. The collection phase covers gathering information on several landscapes as per the concept map including the technology, environmental, competitor, collaborator, geopolitical, and drivers.

The "Execute TRM" function represents the operationalization of the roadmap with the transition from strategic intent to tangible action. As shown in the diagram, this begins with the "Initiate TRM Execution Cycle" function, which orchestrates the concurrent execution of multiple roadmap-guided development streams. These include the monitoring trends and drivers, development of capabilities, products, technologies, research, and the allocation of resources, each derived from the corresponding TRM layer at time [n]. These streams operate in parallel, reflecting the integrated and cross-functional nature of roadmap implementation. The outcome of these concurrent processes is an updated state for each roadmap layer (at time [n+1]), which collectively informs future TRM updates. Importantly, this structure models how real-world execution spans multiple domains.

Within the MBSE-TRM lifecycle, "Execute TRM" runs concurrently with the "Monitor TRM" function. This reflects the real-world dynamic where roadmap execution does not pause during updates or monitoring activities. While the roadmap may evolve through monitoring and periodic revisions, execution proceeds based on the most recently consolidated TRM baseline, ensuring continuity of effort while allowing for adaptability.

Execution also serves as a critical source of feedback into the roadmap lifecycle. As projects are implemented, real-world progress, delays, resource bottlenecks, or unexpected technical challenges may surface, all of which inform future updates to the TRM. This feedback mechanism underscores the importance of tightly coupling execution with monitoring and evaluation processes.

No domain-specific SysML profile extensions were employed in this work. The MBSE-TRM framework intentionally operates using standard SysML constructs to preserve generality and reusability across application domains. The development of specialized SysML profile extensions for EW-specific modeling, such as signal processing chains or countermeasure behaviors, is identified as a potential area for future work.

The formalization of the MBSE-TRM framework using SysML provides a structured and semantically consistent representation of the TRM lifecycle, its underlying processes, and interdependencies. Through the use of physical and function diagrams, the framework supports traceability from external triggers to roadmap creation, execution, monitoring, and iterative updates. The use of SysML not only enhances clarity and rigor but also enables integration with broader MBSE practices. This formal model serves as a foundational artefact for implementing TRM processes within complex, multi-stakeholder environments, ensuring alignment between strategic intent and technology execution over time. The next section validates the framework by applying it to the domain of EW against radar.

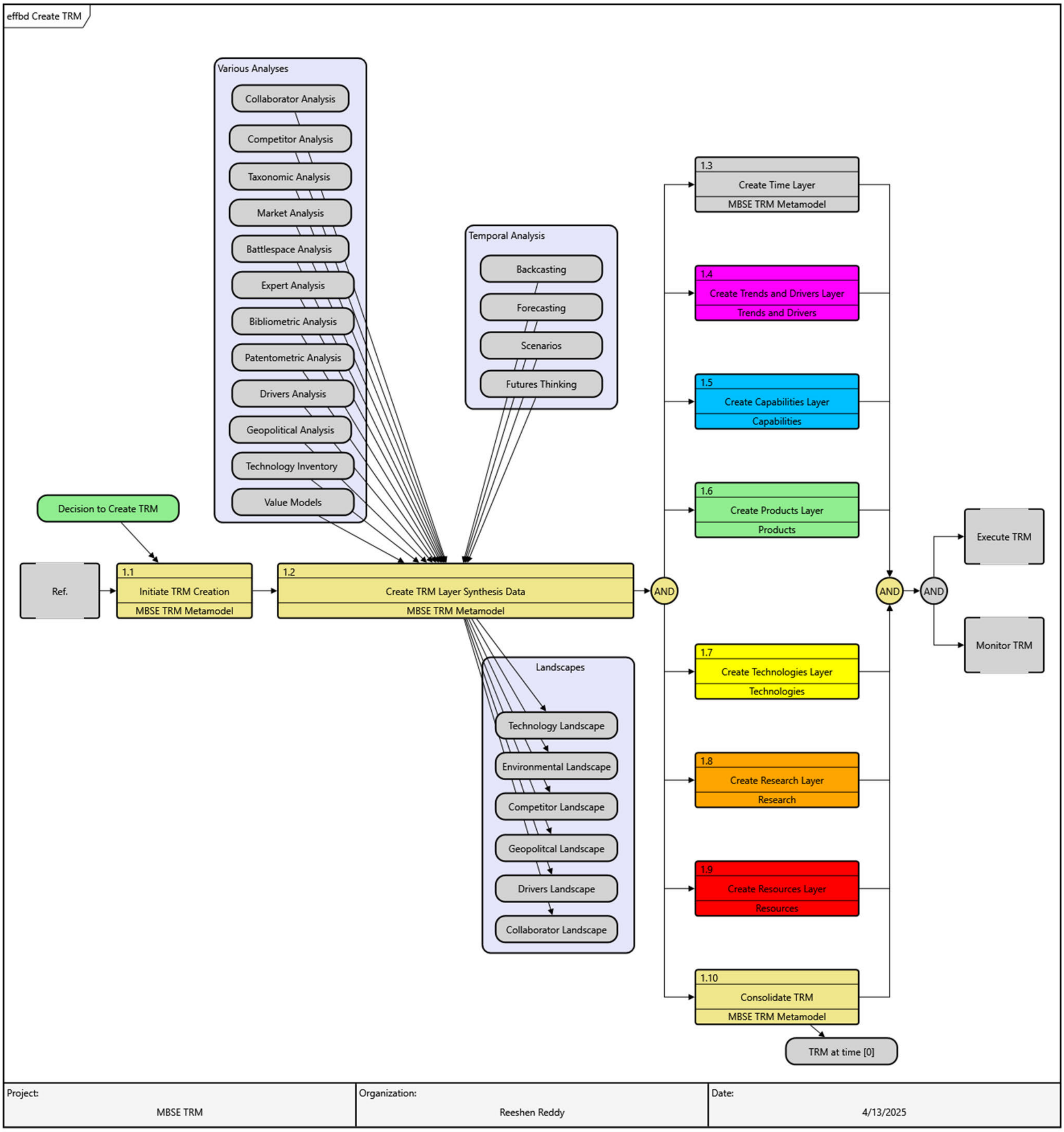

FIGURE 6. **eFFBD for create TRM.**

V. APPLICATION TO EW INNOVATION STRATEGY

A. MAPPING TO MBSE-TRM

To validate the MBSE-TRM framework, EW against radar systems was selected as a test case owing to its high technology intensity, rapid innovation cycles, and strategic importance. This application builds on two prior contributions: (i) [30] that examined the implications of Industry 4.0 on EW innovation and motivated the inclusion of a capability layer in roadmaps, and (ii) a comprehensive state-of-the-art review of EW against radar systems in [41] that synthesized more than 10,000 open-source items through bibliometric and patentometric analysis. The purpose here is not to repeat those analyses, but to demonstrate how the MBSE-TRM framework systematically structures such knowledge into architectural and roadmap artefacts, thereby validating its utility for technology-intensive domains. Fig. 9.

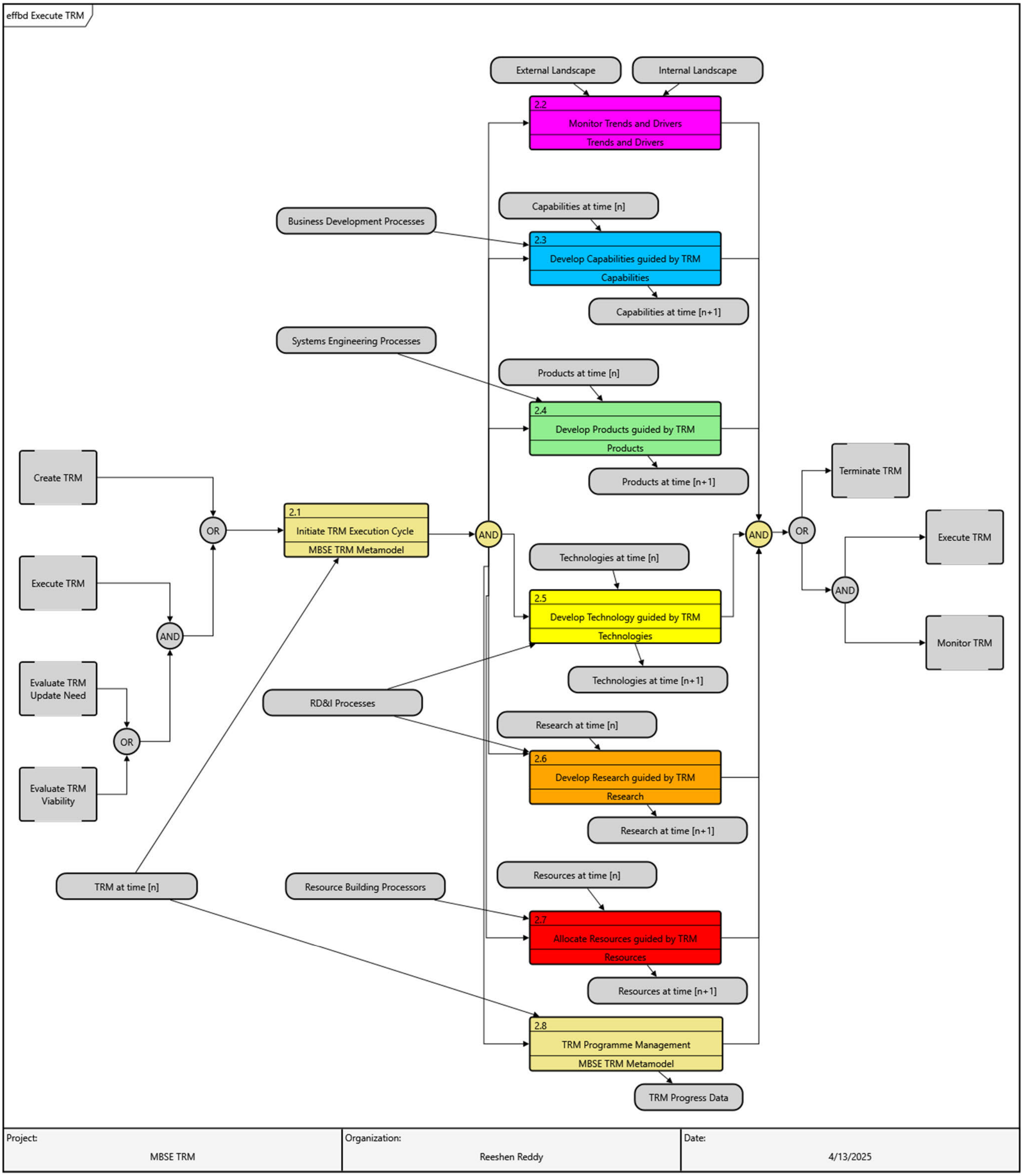

FIGURE 7. eFFBD for execute TRM.

visually delineates the subset of the MBSE-TRM metamodel that is applied using a dashed red line.

In the MBSE-TRM metamodel, several other analyses are noted such as competitor analysis and driver analysis which tend to become company and product specific. While the full framework includes broader aspects such as competitor analysis, commercialization strategy, and value modelling, the technological analyses subset is

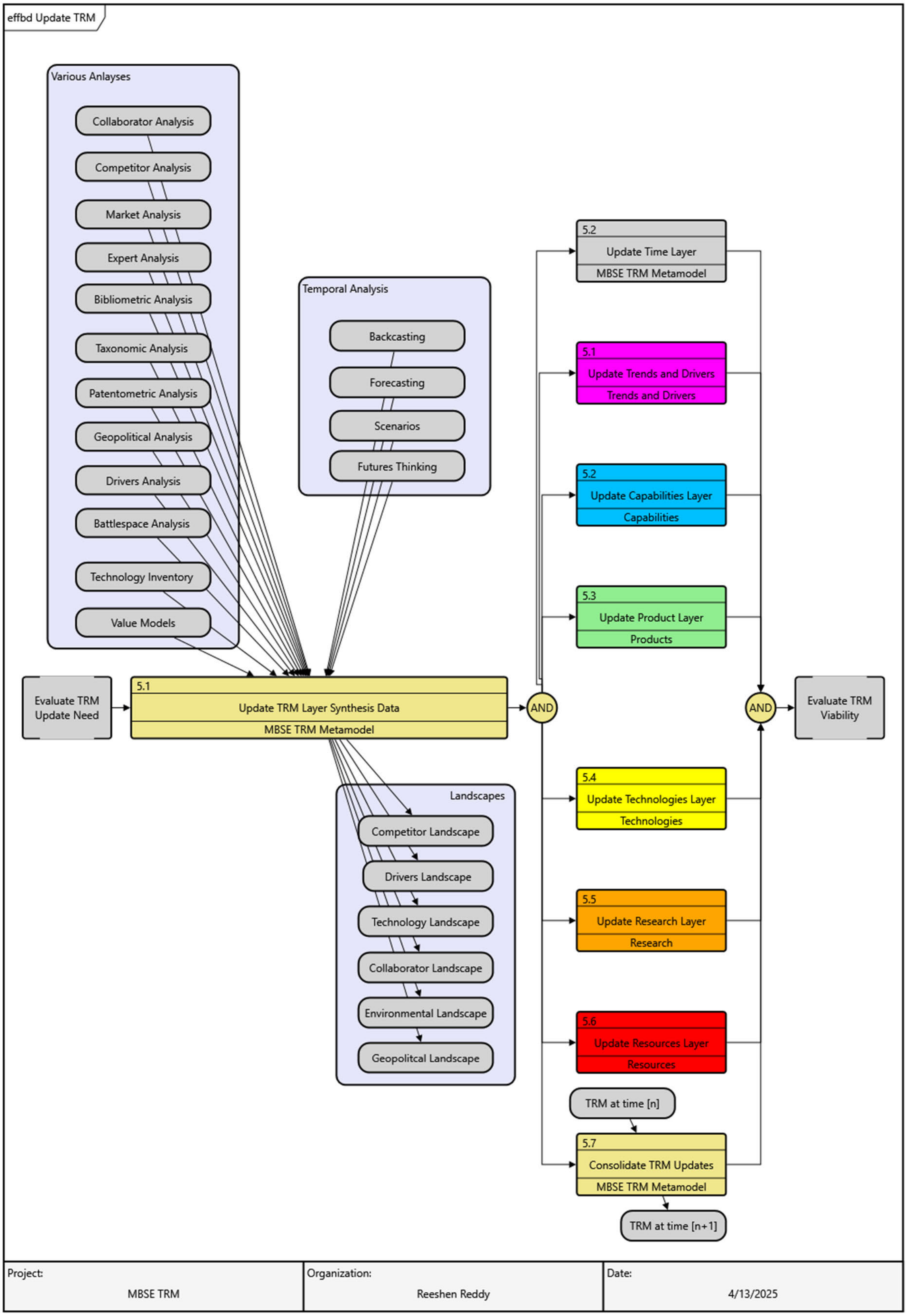

FIGURE 8. eFFBD for update TRM.

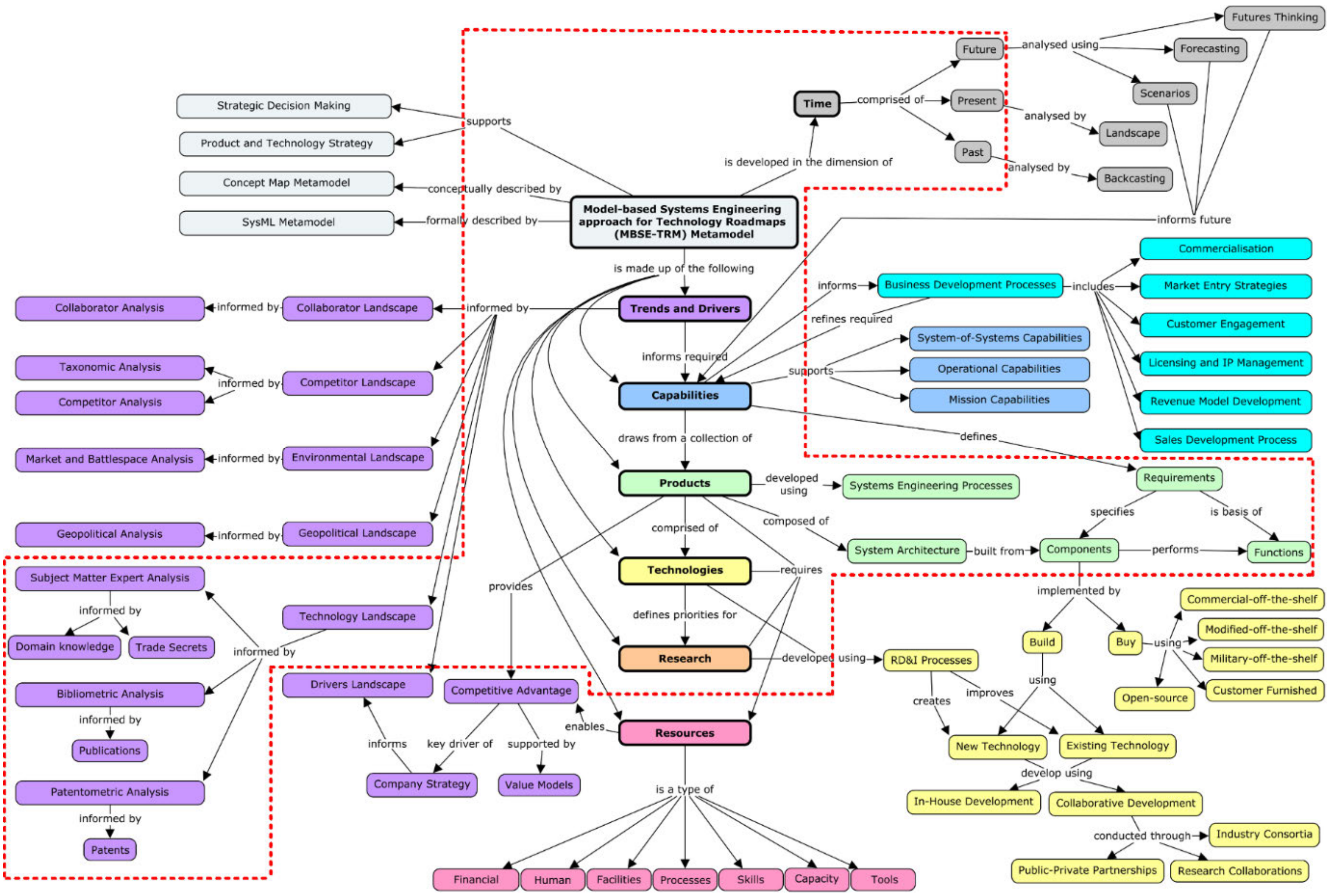

FIGURE 9. Concept map that delineates the subset of the MBSE-TRM applied.

applied to various roadmap layers including "Trends and Drivers", "Capabilities", "Products", "Technologies", and "Research" for a technology-focused roadmap development. The "Resources" layer is also highly context and company specific and therefore, excluded. In the review in [41], quantitative analysis of EW against radar including bibliometric, patentometric and cluster analyses was conducted. Furthermore, complementary qualitative analysis, including taxonomic classification of EW system types and roles and critical appraisal of advancements in architectures and algorithms. Together, these analyses represent a lens into the state-of-the-art advancements in EW against radar systems and algorithms, shedding light on the current landscape of research and innovation and maps to the formation of the "Technology Landscape" in MBSE-TRM.

Building on this foundation, using the MBSE-TRM framework, and leveraging prior contributions, a notional next-generation EW architecture and a strategic roadmap for its realization is synthesized that can be used by researchers to guide the development of innovative EW technologies and methodologies and by EW practitioners to inform system design, operational deployment, and capability enhancements. The term "notional" is intended to indicate that the EW architecture and a strategic roadmap presented here are strategic constructs which are thematic in nature and intended to provide a strategic direction rather than being prescriptive. The tailoring of the MBSE-TRM framework for EW against radar systems, undertaken in this research to focus on technological aspects and avoid company-specific and classified information, serves as a pragmatic example of how the framework can be customized. In real-world scenarios, it is expected that the MBSE-TRM framework will be tailored to suit specific organizational, operational, or technological contexts. Furthermore, the framework may be extended in ways not originally anticipated, reflecting its extensibility and adaptability.

A distinguishing feature of the MBSE-TRM framework is its explicit treatment of the time dimension, spanning the past, present, and future with consideration of the MBSE-TRM lifecycle. This temporal structuring allows roadmap elements to be aligned not only hierarchically but also chronologically, enabling foresight and staged planning. In the context of EW against radar, where threat environments evolve rapidly and technological innovation cycles are accelerating, the ability to sequence developments over time, while remaining adaptive, is essential. The notional architecture and roadmap that follow span this temporal continuum, with the "present" representing the point of analysis during the writing of this

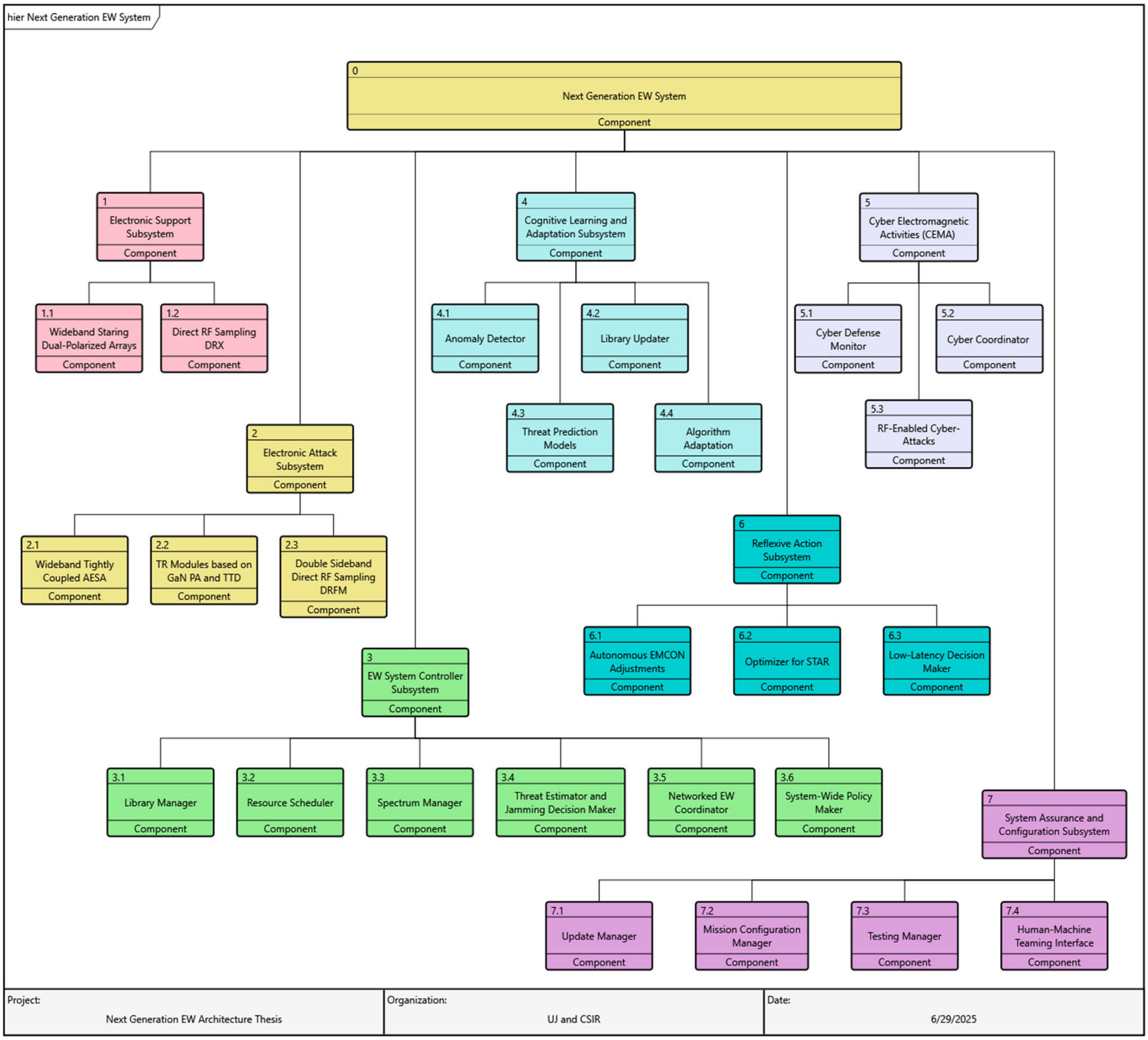

FIGURE 10. Notional next-generation EW architecture.

research. The notional requirements identified in [41] map precisely to the MBSE-TRM "requirements" block. They are not repeated here in full but a cursory account to show validation using MBSE-TRM. The requirements are stated with a closed box systems view, omitting measurable metrics to retain generality while allowing flexibility for diverse implementation contexts. These notional requirements are general in nature and would be defined by EW "capabilities" block in MBSE-TRM including stand-off, stand-in, self-protection, or escort roles, for tactical and/or strategic EW applications. Within MBSE-TRM, these requirements, captured in Vitech GENESYS, validate the framework's ability to capture critical needs for next-generation EW systems, including:

- Multi-domain synchronization: operations coordinated across land, sea, air, space, and cyber domains.
- Autonomy and teaming: integration of autonomous platforms and human–machine collaboration for time-sensitive decision-making.
- Resilience in contested spectrum: dynamic spectrum management and adaptability to congested, contested, constrained environments.
- Modularity and upgradeability: architecture that accommodates rapid software and hardware insertion without full redesign.
- Cognitive and cyber-electromagnetic integration: leveraging AI and cyber-EW convergence for anticipatory and adaptive responses.

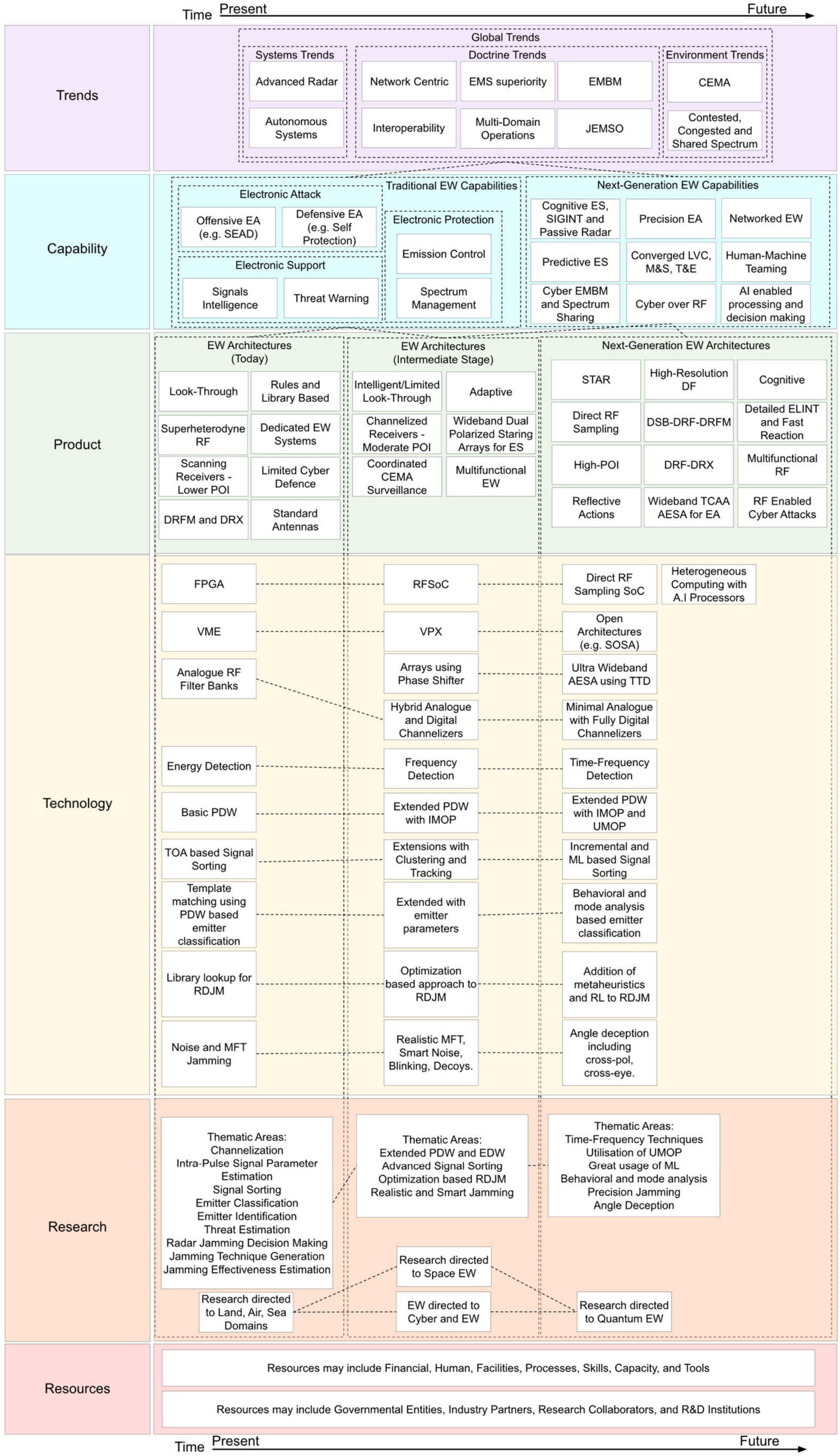

FIGURE 11. Notional TRM for next-generation EW roadmap.

These requirements, captured in Vitech GENESYS, illustrate how MBSE-TRM links abstract capability needs with roadmap layers, reinforcing its role as a structured, system-oriented framework for technology strategy. The notional next-generation EW architecture shown in Fig. 10 maps the MBSE-TRM ''system architecture block''.

Readers are referred to [41] for an in-depth discussion of the architectural considerations. In summary, the architecture is designed to achieve high probability of intercept (POI), defined here as the ability to intercept radar emissions with high confidence across wide frequency, spatial, and temporal coverage, alongside precision electronic support, precision electronic attack, adaptive prediction, and system wide control and orchestration to achieve resilience for mission execution.

B. NOTIONAL NEXT-GENERATION EW ROADMAP

A notional strategic roadmap for next-generation EW against radar is shown in Fig. 11 drawing from the roadmaps in [30] and [41] and mapped using the MBSE-TRM framework in a multi-layer format. The roadmap is not prescriptive but thematic, providing strategic direction that can be tailored for specific organizational or classified contexts with a focus on technological aspects.

The Trends layer highlights contested and congested spectrum, the rise of joint electromagnetic spectrum operations (EMSO)/electromagnetic battle management (EMBM), multi-domain operations, and the growing role of AI and autonomy. The Capability layer emphasizes predictive electronic support, precision electronic attack, fusion of passive sensing, and human-machine collaboration. These capabilities guide phased product transitions from legacy architectures based on VME and superheterodyne receivers, through intermediate VPX/RFSoC-based systems, toward next-generation direct RF sampling and cognitive architectures. The Technology layer reflects enabling advances in ML-based detection and jamming, wideband digital arrays, heterogeneous computing, and emerging paradigms such as quantum radar and cyber-EW convergence.

While this roadmap illustrates a transition to advanced, AI-enhanced and modular architectures, key challenges remain ensuring generalization of algorithms to operational conditions, reducing computational complexity, and managing spectrum in highly dynamic environments. Beyond technology, the increasing autonomy of EW systems raises issues of compliance with international law, cybersecurity, and spectrum deconfliction policy implications.

The notional EW architecture corresponds to the Product layer of the MBSE-TRM framework. In this context, ''architecture'' is treated as the system-level representation of potential product configurations rather than a single implementation. It therefore serves as a design abstraction from which multiple EW products, such as stand-off jammers, stand-in decoys, or self-protection suites, can be derived. This maintains direct traceability to the MBSE-TRM hierarchy, where Products provide the link between Capabilities and enabling Technologies.

AI-enabled EW architectures are expected to exhibit adaptive and evolving behavior over time as threat environments and operational conditions change. In such contexts, AI-based analysis agents may act as sources of evidence that inform roadmap reassessment by identifying emerging performance trends, capability gaps, or shifts in threat characteristics. Within the MBSE-TRM framework, these insights are incorporated through existing lifecycle feedback and update trigger mechanisms, rather than through direct real-time operational integration. This preserves structured governance and traceability while enabling more responsive and informed roadmap evolution in fast-evolving EW contexts.

This strategic roadmap, grounded in the MBSE-TRM framework, exemplifies how structured, model-based reasoning can be applied to synthesize emerging trends, evolving capabilities, and architectural trajectories into a coherent, forward-looking strategy for next-generation EW systems. Through this mapping, the MBSE-TRM framework is validated as a means of transforming diverse EW knowledge into structured, model-based artefacts that preserve traceability and abstraction.

VI. DISCUSSION AND CONCLUSION

A. LIMITATIONS, ASSUMPTIONS AND SCOPE DELIMITATIONS

This research is subject to several limitations and assumptions, and specific delimitations were introduced to intentionally bound its scope. A summary is provided below:

•Assumptions: The MBSE-TRM framework is assumed to adequately capture expert mental models and the tacit logic commonly applied in technology roadmap development. It is further assumed that SysML provides an appropriate formalism for representing the structure and behavior of a TRM.

- Limitations: Validation of the MBSE-TRM framework was restricted to the domain of EW against radar.
- Delimitations: The research intentionally focused on the technological dimension of roadmapping, excluding organization-specific factors such as competitor analysis, resource allocation, and commercialization strategy.

Despite these boundaries, the findings offer a valuable foundation, demonstrating the feasibility of a model-based approach to technology roadmapping and providing a platform for future extension into classified, organization-specific, and multi-dimensional contexts.

A. IMPLICATIONS ON THEORY AND PRACTICE

The MBSE-TRM framework advances the theory in the field of strategic technology management, technical roadmapping and systems engineering by formalizing a model-based TRM framework that includes a metamodel formalized into a reusable schema together with the associated semantics (meaning) and syntax (structure and form) using SysML in Vitech GENESYS.

Traditional roadmapping often lacks structured methodologies, relying on ad-hoc processes. While the lack of formality aids in the versatility, it can lead to inconsistencies and the quality of output based on the skill of the strategy practitioner. MBSE-TRM addresses this gap by introducing a formalized TRM structure based on the multi-layered technology roadmap with qualitative and quantitative inputs.

Furthermore, a dynamic systems view is adopted on the TRM with consideration of the TRM lifecycle. Importantly, the MBSE-TRM structure is not static and supports dynamic evolution over time. This adaptability is explicitly captured in behavioral diagrams, which model the execution and maintenance of the TRM across its lifecycle. These characteristics are essential for a technology roadmap that must adapt to fast-changing contexts such as EW. Collectively, the physical block diagram, hierarchy diagram, and BDD represent a cohesive and semantically rich structure that underpins the dynamic behavioral views.

While the structural model defines the foundational elements of the MBSE-TRM framework, the behavioral view captures how these elements are operationalized across the technology roadmap lifecycle i.e. the logical architecture. The top-level behavioral or functional view begins with the MBSE-TRM lifecycle that models the processes of roadmap creation, execution, monitoring, and iterative refinement. Practitioners of TRM may adopt MBSE-TRM and tailor to company or classified contexts.

Additionally, there is limited theory and information in the public domain on EW strategy. The application of MBSE-TRM to EW against radar represents a framework to guide the research and development of innovative EW technologies and methodologies, and EW practitioners can use to inform system design, operational deployment, and capability enhancements. Practitioners of EW may also tailor for company or classified contexts.

The success of TRM, particularly in domains such as EW, relies not only on technical factors but also on alignment with geopolitical developments, socio-political trends, and techno-economic shifts. A community of practice is recommended that includes policy makers, practitioners, strategists, and researchers serving as a collaborative forum to continuously refine, contextualize, and validate technology roadmaps within real-world constraints and opportunities.

B. IMPLICATIONS ON POLICY

The MBSE-TRM framework, as a strategic management tool, has potential to be adopted by policy makers for integrating systems engineering with strategic planning across defense and civilian sectors. By embedding MBSE-TRM in defense planning, policymakers can align technological advancements with strategic objectives, enhancing national and regional security in the electromagnetic battlespace.

From an EMSO and EW specific lens, the MBSE-TRM framework applied to EW including notional next generation EW architecture and roadmap provides a structured framework for achieving spectrum dominance. Defense communities such as the SADC and NATO may adopt MBSE-TRM to develop region specific and classified EW strategies. The reliance on open-domain data also demonstrates an approach where a strategic direction that is unclassified can be created to drive direction of industry, R&D organizations, acquisition agencies and academia. Specific programs can then decompose and tailor into roadmaps with architectures with more detail in classified or proprietary environments. This layered approach highlights the importance of governance mechanisms that explicitly manage the interface between open-domain abstractions and classified program-level detail. By maintaining traceability across these boundaries, MBSE-TRM enables policymakers to guide strategic intent and technological direction while preserving security, sovereignty, and compliance with classification constraints.

The growing complexity of EW systems and spectrum sharing requirements underscores the need to align emerging architectures with international spectrum governance frameworks such as those defined by the International Telecommunication Union (ITU) and operational EMSO doctrines.

C. IMPLICATIONS ON FURTHER RESEARCH

This paper established the MBSE-TRM framework and applied the framework to EW against radar. Several future research directions emerge. The MBSE-TRM framework may be expanded to include scenario-based roadmaps in more depth. The metamodel and formal SysML model of MBSE-TRM includes temporal characteristics for generalization to scenario-based roadmaps and futures thinking paradigms. However, this area of MBSE-TRM framework can be expanded upon to incorporate the handling of multiple probable future scenarios and planning TRM development and execution accordingly.

Strategic technology management has emerged to manage and direct technology to support innovation with over 315 tools used in practice [42]. TRM has emerged as a very popular framework due to its simplicity, transparency, modularity, flexibility, and extensibility. However, the author postulates the underlying ontology, uncovered and formalized for MBSE-TRM is extensible to many other strategic technology management tools. It is envisioned that a model-based strategy metamodel can be developed that generalizes to MBSE-TRM and many other strategic technology management tools.

The MBSE-TRM framework developed, and its subsequent application leveraged several distinct tools that required manual expertise to link together. Similar to the role that tools such as Vitech GENESYS fulfils in MBSE, it is envisioned that a digital roadmapping tool that implements the

MBSE-TRM schema, semantics and syntax could be developed that also incorporates interfaces to tools for quantitative and qualitative analysis. Furthermore, such tools could include automatic diagram generation from the underlying semantic model. Digital roadmapping tools could also include design aids to assist practitioners with controlling various human-intensive tasks in the MBSE-TRM process such as balancing capturing breadth and maintaining specificity in quantitative analyses.

The MBSE-TRM framework developed was validated for EW against radar using publicly available data. Validation with more real-world data including classified and proprietary data would further strengthen the robustness of the framework. Despite the exclusive use of publicly available data, the MBSE-TRM framework was established using principles from systems engineering and technology strategy. The validation of MBSE-TRM for EW against radar leveraged over 10,000 primary sources, providing grounding in statistically significant dataset, aligned with Industry 4.0 big data analytics. The notional next-generation EW architecture and roadmap were intentionally kept at a high level of abstraction to preserve validity while avoiding sensitive details.

The research focuses on technological aspects using information in the open domain with emphasis on validation using EW against radar. Extension of this research to EW against communications, cyber and GNSS would represent a richer and more complete view of EW strategy. Furthermore, this research focused on the technological aspects of the field of EW against radar and could be extended to include human factors, humanities, psychology, sociology, cultural, and ethical factors to represent a more holistic lens of EW. The notional next generation EW architecture and roadmap present several future work directions for next-generation EW systems.

Beyond EW, similar technology evolution and integration challenges arise in other complex, tightly constrained system domains such as cybersecurity, satellite systems, and AI/ML-driven systems. Recent work in small satellite systems, for example, demonstrates the joint consideration and integration of multiple subsystem technologies such as sensing, actuation, embedded control, and lifecycle phase requirements within a single design effort, which could be systematically supported by the proposed MBSE-TRM framework [43], [44].

Furthermore, established capability-based frameworks such as the U.S. DoD DODAF, the U.K. Ministry of Defense's "TEPID-OIL" construct [45], and South Africa's "POSTEDFIT" model [46], provide enterprise-level structures for capability planning and acquisition. While the MBSE-TRM operates at a complementary level of abstraction, focusing on the temporal evolution of markets, products, technologies and their interdependencies, it can be conceptually aligned with these architectures. Future work should explore the integration of MBSE-TRM within capability-based planning architectures to strengthen traceability between technological innovation, resource allocation, and capability realization. Such integration, supported by expert engagement, would enhance both the theoretical robustness and practical adoption of MBSE-TRM in defense and other technology-intensive sectors.

This research demonstrates the value of MBSE-TRM as a structured, model-based approach to technology roadmapping, enabling rigor, traceability, and adaptability in strategy for technology-intensive domains. In doing so, it not only advances the practice of roadmapping, but also aligns with the principles of Industry 4.0 and the emerging vision of Industry 5.0, providing a bridge between model-based engineering and the dynamic demands of future innovation ecosystems.

D. CONCLUSION

Technology-intensive industries increasingly face environments of constant and systemic change, where geopolitical, technological, and market disruptions arise faster than traditional planning cycles can adapt. Managers in these domains must recognize that innovation now requires tools that adopt a systematic systems-level approach, capable of linking strategic intent to evolving technologies while retaining flexibility. Technology roadmaps remain one of the most widely used instruments for aligning markets, products, and technologies. However, current practice remains largely static, workshop-based, and dependent on subject matter experts, which limits consistency, traceability, and reuse. In an era where one disruption is quickly replaced by another, this reliance on fixed, document-based tools constrains strategic agility. The MBSE-TRM framework presented in this paper responds to these challenges by embedding the rigor of systems engineering into roadmapping. The managerial relevance lies in enabling organizations, particularly in technology-intensive sectors such as defense and advanced manufacturing, to create roadmaps that are both rigorous and dynamic. Instead of being one-off exercises, roadmaps become living models that can adapt to shifting drivers, emerging technologies, and organizational priorities, supporting more transparent, agile, and resilient innovation strategies.

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