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Visualization Approach for RAMI 4.0 Value Chain Analysis

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ABSTRACT Industry 4.0 has revolutionized industrial automation, with models, such as Industry 4.0 Reference Architectural Model (RAMI 4.0), providing a structured framework for optimizing value chains and processes. However, the complexity and abstract nature of RAMI 4.0 have limited its practical application, especially due to the lack of clear visualization methods to understand industrial ecosystems. Effective visualization is essential to translate this framework into actionable insights, enabling stakeholders to grasp system interactions, dependencies, and value-creation processes. This article proposes a multidimensional visualization approach, illustrated through a smart heat pump example, to map information and operational technologies, their interactions, and value chains. Combining 3-D visualizations for integrated system overviews with 2-D visualizations for task-specific analysis, the approach provides a comprehensive understanding of RAMI 4.0 value chains, enabling stakeholders to address their analytical needs with clarity. It facilitates run-time value chain analysis, offering real-time insights for decision-making during operations. The approach maps industrial systems across RAMI 4.0 axes and aligns them with engineering processes and lifecycle phases, enabling the exploration of system interactions, dependencies, and stakeholder contributions. This supports the analysis of engineering and business processes, optimizes infrastructure, and facilitates smooth technological transitions. It enhances RAMI 4.0's utility for real-time decision-making and operational efficiency, boosting competitiveness in industrial ecosystems.

INDEX TERMS 2-D and 3-D visualizations, Industry 4.0 (I4.0), lifecycle management, microservice architecture, real-time decision making, run-time value chain analysis, smart industry ecosystems, stakeholder collaboration.

I. INTRODUCTION

The dawn of Industry 4.0 (I4.0) in 2011 transformed the production and automation landscape. It enabled information technology (IT) and operational technology (OT) to communicate directly, creating new opportunities for innovative business strategies in smart industries. This disrupted traditional models, such as the ISA-95 automation pyramid [1], resulting in the development of reference architecture models that help navigate the complexities of the new manufacturing landscape [2]. Many models used in business are theoretical and may not be practical in real-world situations. This can be particularly challenging when it comes to visualizing and analyzing the value chain of a company or a product. In addition, understanding the dynamic interactions between IT/OT systems and value chains within complex networks is still a significant challenge. These networks characterize engineering, operational, and financial processes, and their optimization is key to market competitiveness and profitability [3], [4]. Visualization plays a critical role in addressing these challenges by providing stakeholders with clear, real-time insights into system behavior and operational performance. We propose a multidimensional visualization approach that facilitates the value chain analysis of multistakeholder smart industry ecosystems. This approach offers a comprehensive view of how engineering and business processes integrate across various levels, from field devices to business activities. Based on Porter's [3] value chain analysis methodology, this approach aims to support strategic planning and operational efficiency.

By visualizing these complex relationships, stakeholders can monitor and manage their systems more effectively, enabling real-time decision-making based on run-time analysis of the value chain.

The Industry 4.0 Reference Architectural Model (RAMI 4.0) is a widely recognized framework for designing, implementing, and evaluating I4.0 solutions [5]. It provides a structured way to classify and visualize the various aspects and technologies involved in I4.0, spanning three axes representing the business perspective, product life cycle, and factory hierarchy, respectively. Despite its broad applicability, RAMI 4.0 can be abstract and complex, often lacking practical tools for visualizing and managing interactions within the value chain. As I4.0 continues to evolve, there is an increasing demand for more comprehensive visualization techniques that clearly represent the integration of engineering and business processes with product life cycles [6].

To address these gaps, we introduce visualization techniques aligned with RAMI 4.0 and built on secure microservice architectures. Microservice architecture, characterized by fine-grained, independently deployable services, promotes flexibility, scalability, and maintainability in complex industrial systems [7], [8]. Using microservices, smart industry ecosystems achieve greater modularity and resilience [9]. Microsystems operate autonomously and integrate to create fully automated industrial processes, enhancing flexibility in microservice orchestration [10]. A system-of-microsystems approach ensures that interconnected but independent microsystems perform complex tasks efficiently, improving performance and scalability [11].

This research focuses on two main questions: 1) How can a visualization of the RAMI 4.0 solution space represent IT/OT microsystems within complex multistakeholder smart industry ecosystems? 2) How can we visualize the value chain analysis to manage the interaction between the product life cycles and the engineering, operational, and business processes in such ecosystems?

We propose a multidimensional visualization approach that includes both 2-D and 3-D visualizations to enable the analysis of interactions between IT/OT microsystems and value chains. The purpose of these visualizations is to simplify the complexity of smart industry ecosystems, enabling stakeholders to make informed, data-driven decisions in real time. 3-D visualizations provide an integrated overview of the entire system architecture within RAMI 4.0, whereas 2-D visualizations enable a more focused analysis of specific operational aspects, offering stakeholders a comprehensive solution. The proposed methodology consists of several key steps: validating and mapping industrial systems along the RAMI 4.0 axes, aligning these systems with engineering process phases, and projecting stakeholder contributions and value-addition metrics throughout the product life cycle.

The approach supports the analysis of system interactions and dependencies, helping organizations optimize existing infrastructure while transitioning to advanced technologies, thereby reducing costs and minimizing operational disruptions. In addition, by enabling run-time analysis of the value chain, organizations can better monitor performance and address inefficiencies during the operations and maintenance phases. We illustrated how to apply the approach using a smart heat pump (SHP) use case example, which exemplifies the RAMI 4.0 value chain analysis in action. By visualizing these interactions, stakeholders can gain a deeper understanding of the system, promoting multistakeholder collaboration, sustainable manufacturing, and the deployment of complex I4.0 solutions.

The rest of this article is organized as follows. Section II explains the value chain analysis concept and introduces the RAMI 4.0 value chain analysis. Section III explains the problem and its motivation. Section IV examines related work and identifies knowledge gaps. In Section V, we present our proposed solution and the methodology for our value chain analysis visualization approach. Section VI provides an illustrative example for our approach to RAMI 4.0 value chain visualization using an SHP value chain use case. Section VII provides proof-of-concept implementation (work in progress). Section VIII outlines the strengths and limitations of the approach. Finally, Section IX concludes this article, with potential future research directions, and Appendix A provides the detailed algorithms used in our proposed approach for visualization methods for value chain analysis.

II. RAMI 4.0 VALUE CHAIN ANALYSIS

Porter's [3] value chain analysis provides a framework for companies to assess their operations, identifying activities that add value and contribute to competitive advantage. By integrating financial metrics, such as profit margins and return on investment, organizations can target areas for cost reduction and process improvement. In line with the sustainability goals of I4.0, this analysis extends beyond financial performance to encompass environmental metrics, such as carbon emissions and resource consumption, making it crucial for long-term success and aligning with the demands of eco-conscious stakeholders. RAMI 4.0 is an effective framework for analyzing value chains by examining the flow of materials, information, and costs across production and delivery processes. It helps identify inefficiencies, cost drivers, and potential environmental impacts within industrial ecosystems [12]. In this article, we propose that RAMI 4.0 value chain analysis can be structured along three dimensions: hierarchy levels, life cycle and value stream, and layers. These axes provide distinct perspectives for evaluating and optimizing value-adding activities in smart manufacturing environments. By leveraging digital capabilities from Industry 4.0, this structured analysis supports informed decision-making, enhancing the efficiency and effectiveness of smart industry ecosystems.

1) *Hierarchy Levels:* RAMI 4.0 organizes industrial components across levels, from product to enterprise and connected world. Value chain analysis at these levels helps trace where value is added in the manufacturing process and how I4.0 technologies drive improvements.

For example, at the field level, smart sensors and actuators enhance precision and real-time monitoring. At the enterprise level, strategic data analysis aligns operations with market demands, adding further value.

2) *Life Cycle and Value Stream:* By considering the entire product life cycle, from design development through decommissioning, RAMI 4.0-based analysis tracks how value is added at each phase. During the maintenance and usage phases, for example, continuous data collection can enhance predictive maintenance and future product designs, delivering long-term value to both customers and the business.
3) *Layers:* RAMI 4.0's architecture layers, from asset to business, facilitate analysis of how different functions interact and contribute to value creation. Value chain analysis across these layers identifies opportunities to optimize data flows and processes, enhancing overall system performance. The structured layers allow for clear identification of dependencies and interactions within and across IT/OT systems, ensuring a holistic understanding of system operations.

RAMI 4.0's value chain analysis integrates insights from these three axes to provide a comprehensive view of how value is generated and optimized across a smart manufacturing ecosystem. For example, by analyzing the integration layer in conjunction with the business layer, a manufacturer can improve data exchange across hierarchy levels, enhancing decision-making from the shop floor to executive management. Furthermore, examining the life cycle and value stream axis enables organizations to extend the value stream beyond initial sales, such as through predictive maintenance driven by data analytics. In summary, RAMI 4.0-based value chain analysis empowers businesses to identify opportunities for improved efficiency, responsiveness, and value creation throughout the product or service life cycle. The model's integration of digital capabilities across interconnected layers and levels makes it an essential tool for organizations undergoing I4.0 transformations. However, fully understanding the intricate interactions between IT/OT microsystems and their value chains requires robust visualization techniques. These visualizations can enable stakeholders to assess how each activity contributes to the system's overall performance and sustainability.

III. PROBLEM DEFINITION AND MOTIVATION

RAMI 4.0 offers a structured framework for integrating IT/OT systems within industrial ecosystems, but existing visualization techniques are insufficient to address the complexity of modern value chains, thereby limiting their potential to optimize operations. This limitation underscores the need for a more advanced visualization approach tailored to RAMI 4.0 value chain analysis.

The growing complexity of I4.0 systems, involving interactions between physical assets, digital twins, and stakeholders across multiple dimensions, is not adequately captured by conventional 2-D visualizations. These simplified representations fail to convey critical system dynamics, such as real-time value creation, transfer, and optimization. Effective visualizations play a crucial role by clearly representing these interactions and dependencies, supporting real-time decision-making, and enabling organizations to respond rapidly to evolving system conditions [13], [14]. Existing tools, such as those based on digital twins and asset administration shells aligned with RAMI 4.0 [15], [16], aim to visualize interactions between IT/OT systems. However, they frequently fall short of capturing the complex dependencies and multistakeholder interactions necessary for comprehensive value chain analysis. While these tools may excel at digitizing factories and visualizing asset interactions within lifecycle phases, they often overlook broader system dynamics, such as value chain dependencies in complex manufacturing environments. Despite offering valuable insights into asset management and operations, these tools tend to focus on specific lifecycle phases or asset hierarchies, lacking the integration needed for a holistic analysis of value chain dynamics spanning engineering, operational, and business processes. This limitation complicates efforts to optimize value flows across different hierarchy levels and lifecycle stages, often resulting in inefficiencies, bottlenecks, and reduced competitiveness, particularly in complex supply chains and industrial workflows [3], [17], [18].

Another significant limitation is the insufficient support for multistakeholder analysis. I4.0 environments involve diverse stakeholders, each playing a role at different stages of the value chain. Existing visualization approaches provide fragmented views, making it difficult for stakeholders to align their actions with the overall goals of the system, thus hindering effective collaboration and system-wide optimization [19], [20]. To address this, advanced visualization techniques are needed that not only clarify relationships but also enable run-time analysis of value chains, allowing stakeholders to monitor performance and identify bottlenecks in real-time across all lifecycle stages and organizational levels. Finally, as systems grow in complexity, current visualization methods lack the scalability and adaptability needed to accommodate the increasing number of components, workflows, and stakeholder interactions. This inability to adjust visualizations to reflect evolving system architectures limits the ability to effectively manage and analyze value chains as they expand [13], [21].

These challenges motivate the need for a visualization approach that not only captures the complexity of I4.0 systems but also provides clear depictions of value flows and supports multistakeholder collaboration. By leveraging real-time visualizations, stakeholders can better understand their systems' behaviors and make decisions that optimize value chain performance. Furthermore, such an approach must be scalable and adaptable to ensure that it can evolve with the increasing complexity of industrial ecosystems. Addressing these needs will enable stakeholders to better understand, optimize, and manage value chains within RAMI 4.0 framework, leading to more effective and efficient operations.

IV. RELATED WORK AND KNOWLEDGE GAPS

The RAMI 4.0 framework has been widely studied to integrate IT/OT systems in smart manufacturing. Various research efforts have explored individual layers of the framework, particularly the architecture layers, and their role in facilitating the adoption of I4.0. For example, Ghobakhloo[22] demonstrated the importance of the RAMI 4.0 architecture layer in accelerating the adoption of I4.0 for small and medium enterprises, noting that these enterprises often lack the resources to fully utilize digital models. Piccarozzi et al. [23] showed a positive relationship between the systematic application of the RAMI 4.0 layers axis and improvements in organizational performance, particularly when integrating smart technologies into existing business models. Similarly, Lee et al.[24] emphasized the importance of RAMI 4.0 layers in fostering intelligent data-driven models for smart manufacturing ecosystems. Xu et al.[25] highlighted that restructuring business models in line with RAMI 4.0 is critical for a successful transition to I4.0 environments.

Although these studies underscore the importance of the RAMI 4.0 layers axis, the literature lacks a comprehensive integration of it with the other axes of RAMI 4.0, particularly the engineering and lifecycle phases. Most studies focus on individual layers or phases, creating a fragmented understanding of the entire system. This disconnect hinders the ability to analyze value chains comprehensively, limiting the potential of RAMI 4.0 to fully optimize smart manufacturing processes across all lifecycle phases and hierarchical levels.

Value chain analysis is a critical component of I4.0 optimization, yet its integration with RAMI 4.0 remains underexplored. Existing studies on value chain analysis, such as those by Strange and Zucchella [26], provide insights into the impact of I4.0 on global value chains, but do not address how to connect these insights to the multidimensional structure of RAMI 4.0. Similarly, the authors in [27] and [28] explored value chain optimization in I4.0 contexts, but their approaches do not fully utilize the comprehensive structure of the RAMI 4.0 lifecycle and hierarchical axes These works primarily focus on linear or 2-D analysis of value flows, which are insufficient to capture the complex, dynamic interactions, and interdependencies that exist in smart manufacturing environments.

The current visualization methods within Industry 4.0 frameworks also have limitations when compared to the proposed approach. Traditional 2-D visualizations, such as Gantt charts and Sankey diagrams, are effective in capturing simple workflows, but struggle to represent the multilayered, multidimensional nature of RAMI 4.0 systems [17], [18]. While some CPS-based frameworks offer 3-D visualizations for system components, such as those discussed by Monostori [18] and Wang et al. [29], these approaches are often limited to operational-level interactions and fail to incorporate broader value chain insights. Furthermore, popular product lifecycle management systems, such as those of Siemens and Dassault Systèmes, are effective in managing individual lifecycle phases, but are not equipped with comprehensive visualizations that integrate all phases and stakeholder contributions within the RAMI 4.0 structure [30].

Frameworks, such as Eclipse Arrowhead and future internet-ware (FIWARE), have been developed to facilitate decentralized service orchestration in smart manufacturing environments, offering interoperability between heterogeneous systems [31], [32]. However, these frameworks are primarily focused on service management and communication, rather than detailed value chain analysis within the multidimensional RAMI 4.0 framework. Their emphasis on interoperability does not address the need to visualize and optimize value creation and transfer across lifecycle stages and hierarchical levels.

Digital twin platforms, such as Siemens MindSphere and GE Predix, offer advanced monitoring and simulation capabilities for specific components or processes, but lack the ability to visualize the full complexity of value chain interactions across the RAMI 4.0 axes [33]. Similarly, value stream mapping techniques, which are traditionally used to identify inefficiencies in production workflows, are not suited to the dynamic multidimensional environments of I4.0, where system components and workflows evolve continuously [34].

In contrast, the proposed approach overcomes these limitations by offering a comprehensive visualization framework that integrates all RAMI 4.0 axes into both 2-D and 3-D visualizations. This method supports a detailed value chain analysis, allowing stakeholders to explore system behavior, interdependencies, and value flows with greater clarity and flexibility than current frameworks. The approach is designed to be scalable and adaptable, accommodating the evolving nature of I4.0 ecosystems and supporting multistakeholder environments with customizable and role-specific views. By fully aligning with the RAMI 4.0 framework, this visualization approach enables stakeholders to optimize both operational and strategic decision-making, improving the overall performance and efficiency of smart manufacturing systems.

V. PROPOSED SOLUTION

This section presents a multidimensional visualization approach for RAMI 4.0 value chain analysis, aligned with the I4.0 standard [5], [35]. The purpose of this visualization is to provide stakeholders with actionable insights into complex industrial ecosystems, enabling informed decision-making and optimizing value flows. The proposed solution integrates 2-D and 3-D visualizations to offer comprehensive insights into system behavior, interactions, and value creation processes within the RAMI 4.0 framework. The 3-D visualization leverages all three axes of RAMI 4.0 to provide a holistic perspective on system architecture, revealing patterns, bottlenecks, and optimization opportunities. This enables a deeper analysis of dynamic interactions across multiple dimensions and supports run-time value chain analysis by enabling continuous monitoring of system performance and guiding strategic adjustments during operations.

In addition, 2-D visualizations, such as lifecycle maps, interaction matrices, and cost–value projections, offer simplified, task-specific insights for focused analysis. These 2-D views complement the broader system perspective provided by 3-D visualization, helping stakeholders efficiently manage workflows and assess economic efficiency. The integration of both 2-D and 3-D visualizations provides a robust approach to facilitate real-time analysis and decision-making across the value chain. This combination delivers a detailed understanding of RAMI 4.0 value chains, allowing stakeholders to align their operational requirements with broader system insights. In this section, we outline the design principles, key metrics, detailed methodology, and scalability analysis of the proposed approach.

A. DESIGN PRINCIPLES AND REQUIREMENTS

Heidel [12] and Adolphs et al. [36] explored the life cycle and value stream axis of RAMI 4.0, highlighting the phases products and IT/OT microsystems undergo in their lifetime within engineering and business processes. RAMI 4.0 categorizes these phases into initial (type section) and later (instance section). In addition, microsystems contribute to the production value throughout the life cycle of the product. The product life cycle progresses from requirements through design, engineering, procurement, production, and deployment.

This visualization approach is built around several key principles to ensure effectiveness and ease of use. It emphasizes consistency by providing a uniform visual experience across various systems and phases. The design is user-friendly, making it accessible to both technical and nontechnical users, minimizing the learning curve. Flexibility allows for dynamic adjustments, enabling stakeholders to modify or expand their systems as required. Adaptability ensures it can integrate with evolving technologies and industry-specific needs. Lastly, scalability ensures that the system remains efficient even as complexity and the number of stakeholders grow.

The system requirements are divided into functional and nonfunctional categories. Functional requirements include the ability to visualize microsystem interactions across RAMI 4.0 axes with customizable filters, support workflow, and use case data integration, and provide stakeholder-specific views tailored to individual roles in the value chain. It should also enable collaboration between multiple stakeholders at different organizational levels.

Nonfunctional requirements include the ability of the system to handle large datasets and frequent interactions efficiently, while maintaining an intuitive user interface for both technical and nontechnical users. Security and privacy must be rigorously enforced, particularly in multistakeholder environments, to protect sensitive information. In addition, the system should protect all data and ensure comprehensive privacy measures are in place.

B. DEFINITIONS AND TERMINOLOGIES

Microsystem attributes and microservice interaction tuples comprehensively describe the physical, digital, functional, and operational aspects of each microsystem and their interactions. This approach ensures robust mapping within the RAMI 4.0 framework, capturing the essential details of both individual microsystems and their communications. By aligning these attributes with RAMI 4.0 standards, the approach provides a comprehensive representation of system components and their interactions, facilitating effective integration, performance analysis, and stakeholder management.

1) MICROSYSTEM ATTRIBUTES

A microsystem is defined as a fundamental IT/OT entity characterized by the following attributes.

1) *microsystem.id:* Unique identifier for the microsystem.
2) *microsystem.name:* Name of the microsystem.
3) *microsystem.description:* Description of the microsystem.
4) *microsystem.type:* Category of the microsystem (e.g., field device, control device).
5) *microsystem.role:* Operational role of the microsystem (e.g., data acquisition, processing).
6) *microsystem.asset:* Physical or logical asset associated with the microsystem (e.g., machine, software module).
7) *microsystem.shell:* List of capabilities or functionalities of the physical asset and its digital twin or digital asset represented by the microsystems (e.g., provide communication and data/information)
8) *microsystem.provides:* Services offered by the microsystem (e.g., sensor data, control commands).
9) *microsystem.consumes:* Services required by the microsystem (e.g., input data, external commands).
10) *microsystem_stakeholder.id:* Unique identifier for the stakeholder.
11) *microsystem_stakeholder.description:* Associated stakeholder (e.g., manufacturer, supplier).

2) MICROSERVICE INTERACTION TUPLE

Interactions between microsystems are captured through microservice interaction tuples, which detail the service-oriented connections and consist of following components.

1) *interaction_source.id:* ID of the microsystem initiating the interaction.
2) *interaction_target.id:* ID of the microsystem receiving the interaction.
3) *interaction_source_stakeholder.id:* ID of the stakeholder belonging to microsystem initiating the interaction.
4) *interaction_target_stakeholder.id:* ID of the stakeholder belonging microsystem receiving the interaction.
5) *interaction.services:* Services involved in the interaction (e.g., data sent, commands executed).
6) *interaction.protocol:* Communication protocol used (e.g., OPC UA, MQTT).
7) *interaction.frequency:* Interaction frequency (e.g., periodic, on-demand).
8) *interaction_stakeholder.relationship:* Indicates intra or interstakeholder interaction.

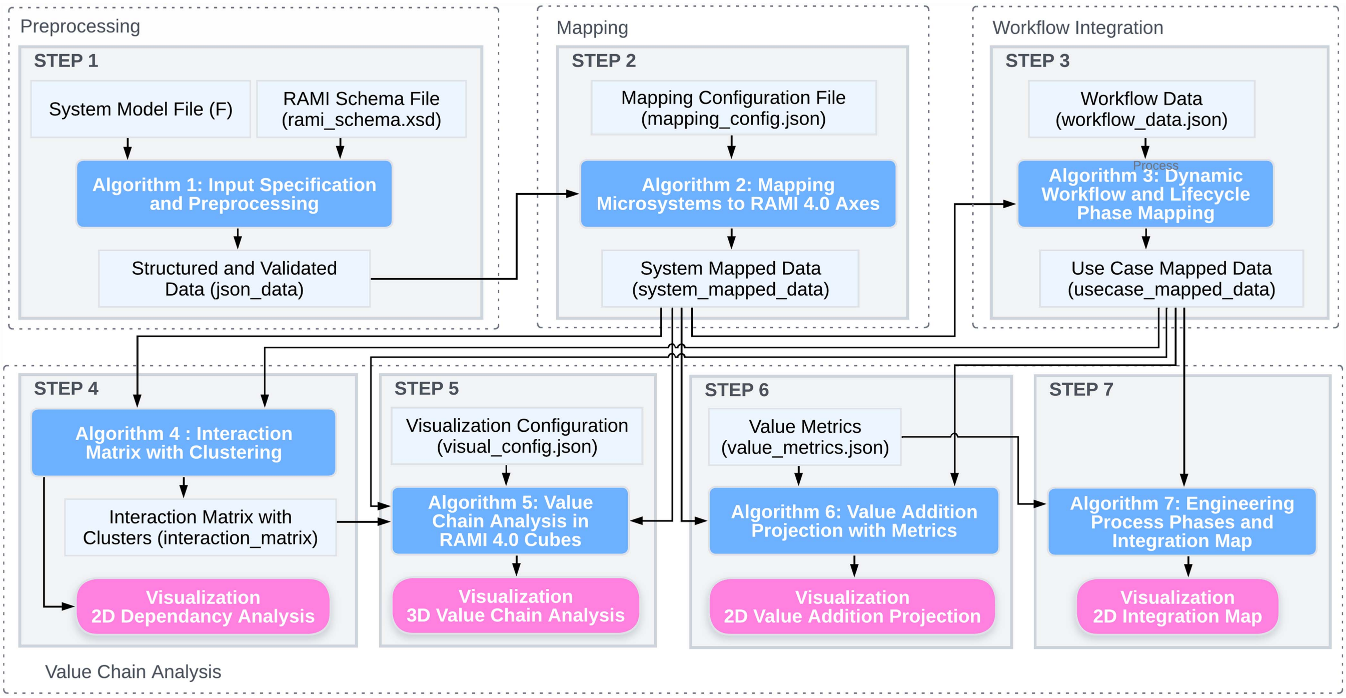

FIGURE 1. Methodology for visualization approach for RAMI 4.0 value chain analysis consisting of seven interconnected steps outlined in detail using algorithms given in Appendix A.

C. METHODOLOGY

This section describes the structured approach for visualizing and analyzing the RAMI 4.0 value chain. It incorporates 3-D and 2-D visualizations to provide a comprehensive understanding of interactions, dependencies, and value additions within smart manufacturing ecosystems. The approach consists of seven steps, as shown in Fig. 1, each contributing to the overall process of preprocessing, mapping, workflow integration, and visualizing and analyzing the value chain within the RAMI 4.0 framework. The examples of the visualizations in the context of this methodology are demonstrated in Section VI using an illustrative example of the SHP use case. Furthermore, the algorithms detailing each step of the methodology are provided in Appendix A, enabling a deeper understanding of the computational processes and logic supporting the visualizations. These algorithms serve as tools to generate visualizations that facilitate the representation of IT/OT microsystems and their interactions across lifecycle phases. GitHub links for their implementations are provided as footnotes in Section VI. These visualizations support value chain analysis and decision-making in complex multistakeholder ecosystems.

Step 1—Input Specification and Preprocessing: The first step of the methodology focuses on the specification and preprocessing of input data, typically represented in domain-specific languages (DSLs). Using Algorithm 1 from Appendix A, the input data are parsed and validated against a predefined RAMI 4.0 schema. This ensures that the data conform to the required structural standards essential for the next stages of the methodology. The preprocessing includes error handling for schema validation failures, prompting users to correct any issues before proceeding. After validation, the data are transformed into a structured javascript object notation (JSON) format, ensuring consistency across the system and facilitating smooth integration into subsequent analysis and visualization processes. This step establishes the foundation for accurate data handling, ensuring that all subsequent operations adhere to schema-compliant inputs. This step is critical to maintaining the integrity of the entire value chain analysis.

Step 2—Mapping Microsystems to RAMI 4.0 Axes: In this step, Algorithm 2 maps microsystems onto the three axes of the RAMI 4.0 cube: hierarchy levels (X-axis), lifecycle stages (Y-axis), and architecture layers (Z-axis). The mapping is conducted using a rule-based approach, with predefined rules governing each axis, and user inputs applied dynamically when no rule matches. For instance, the X-axis coordinate (hierarchy level) is determined by applying rules based on the microsystem's type and role

$$x_m = f_x(\text{microsystem.type}, \text{microsystem.role}, \psi_{\text{hierarchy}}) \tag{1}$$

where $\psi_{\text{hierarchy}}$ is the rule set for mapping to the X-axis. If no rule matches, the algorithm prompts the user to provide input, and this input is incorporated into the rule set

$$x_m = \begin{cases} \psi_{\text{hierarchy}}(a, b), & \text{if match found} \\ \text{PromptUserForMapping}(a, b), & \text{if no match found.} \end{cases} \tag{2}$$

The algorithm applies similar rule-based mappings for the Y-axis (lifecycle stage) and Z-axis (architecture layer), using the microsystem's provided/consumed services and shell attributes, respectively.

This rule-based and user-interactive mapping process ensures that each microsystem is accurately positioned within the RAMI 4.0 cube, enabling stakeholders to visualize and analyze the system's structure and interactions. The flexibility of incorporating user-defined rules allows for continuous adaptation and refinement of the mapping as new microsystems or configurations are introduced.

Step 3—Dynamic Workflow and Lifecycle Phase Mapping: Once microsystems are mapped, Algorithm 3 introduces dynamic filtering, allowing specific workflows or lifecycle phases to be mapped onto the RAMI 4.0 axes. By selecting a workflow w with associated services S_w, the system filters out irrelevant microsystems using the following set-based filtering process:

$$M_w = \{m \in M \mid (\text{microsystem.provides}_m \cap S_w \neq \emptyset) \vee (\text{microsystem.consumes}_m \cap S_w \neq \emptyset)\}. \quad (3)$$

This step supports targeted analysis by enabling stakeholders to visualize microsystems relevant to specific operational scenarios. The algorithm allows for both granular and system-wide views by dynamically filtering out irrelevant components. Stakeholders can visualize interactions within specific workflows or focus on lifecycle phases critical to the analysis. This flexibility reduces complexity in the visualization and enables stakeholders to concentrate on the microsystem interactions that drive the value chain within a defined context.

Step 4—System-of-Microsystems Interaction Matrix with Clustering: In the fourth step, Algorithm 4 constructs a 2-D interaction matrix to capture the relationships and communication pathways between microsystems. Microsystem interactions are analyzed for density, allowing the algorithm to identify clusters of microsystems with high interdependency. These clusters are assigned unique cluster IDs, which will be used in the following steps to organize the RAMI 4.0 cube visualization effectively. To manage complexity, we suggest using clustering techniques with a dependency structure matrix (DSM) approach to group microsystems into clusters based on interaction density [37], [38], [39]. This clustering can rearrange the microsystems in the interaction matrix and group highly interactive microsystems, ensuring that those with the strongest interdependencies are placed within the same RAMI 4.0 cube. This approach helps reduce visual clutter, enabling stakeholders to focus on key areas of high interaction while maintaining a broader system view. Designing the DSM clustering approach specific to this approach is beyond the scope of this article and can be part of future work. The algorithm supports visualizing either the entire interaction matrix or specific clusters of microsystems, allowing stakeholders to focus on areas of the system where optimization or intervention may yield the greatest impact.

Step 5—3-D Visualization of Microsystems in Stakeholder RAMI 4.0 Cubes: In this step, Algorithm 5 provides a 3-D visualization of the system, with microsystems represented as ellipsoids positioned within the RAMI 4.0 cube. The positioning is based on the X, Y, and Z coordinates from Step 2. The algorithm computes the spatial density of microsystems at each coordinate to address overlapping issues by adjusting the size and position of ellipsoids accordingly using the following approach similar to Ester et al. [40] and Ankerst et al. [41]. For clusters with low density, all microsystems are placed within a single cube, while high-density clusters are divided into smaller subclusters to ensure scalability. The microsystem representation adjusts dynamically based on user-defined thresholds, allowing for clear visualizations even in dense regions of the cube. The spatial density n_m at each coordinate is calculated as

$$n_m = \sum_{k \neq m} \delta_{\text{prox}}(m, k) \quad (4)$$

where $\delta_{\text{prox}}(m, k) = 1$ if microsystems m and k are within a predefined proximity threshold. The size s_m and offset δ_m are dynamically adjusted

$$s_m = \frac{1}{1 + \alpha(n_m - 1)}, \quad \delta_m = \epsilon \times (n_m - 1). \quad (5)$$

Interactive features, such as zooming, rotation, and dynamic filtering, allow stakeholders to explore different system perspectives and isolate specific workflows or subsystems for detailed analysis. This 3-D visualization offers a comprehensive view of the system's architecture, supporting high-level value chain analysis by illustrating the flow of value between different hierarchical levels, lifecycle stages, and stakeholders.

Step 6—RAMI 4.0 Value Addition Projection: This step uses Algorithm 6 to map key value metrics, such as cost, profit, environmental impact, etc., for each microsystem onto a 2-D plane, as seen from the top view of RAMI 4.0. This allows for a clear visualization of the contributions of each microsystem across hierarchy levels and lifecycle phases. The value-added, such as profit p_i and cost c_i, incurred by each microsystem m_i, are calculated using

$$\text{value}_i = f_v(p_i), \quad \text{height}_i = \sum_{k=1}^{i} f_v(p_k) \quad (6)$$

$$\text{cost}_i = f_c(c_i), \quad \text{cost\_height}_i = \sum_{k=1}^{i} f_c(c_k). \quad (7)$$

The position of each microsystem in the 2-D plane reflects its contribution to both the hierarchy and lifecycle planes. By visualizing the cumulative flow of value added and engineering costs across lifecycle phases and hierarchical levels, this algorithm identifies critical points of high cost, inefficiency, or environmental impact. This data-driven visualization enables stakeholders to make informed decisions to optimize the value chain, reduce costs, and enhance sustainability.

Step 7—Engineering Process Phases and Product Lifecycle Integration Map: In this step, Algorithm 7 constructs a 2-D integration map T that aligns engineering process phases with product lifecycle stages, capturing stakeholder involvement and system component interactions. The involvement of stakeholders is represented in a binary format, as seen in the figure, where a stakeholder is either involved or not involved in a particular phase or lifecycle stage. The interaction between stakeholders and system components σ_i across lifecycle stages γ_j is captured through the matrix

$$T_{s,\lambda_j} = \sigma_i(s, \gamma_j) \quad (8)$$

where T_{s,λ_j} represents the involvement of stakeholder s in engineering phase λ_j, and $\sigma_i(s, \gamma_j)$ indicates the involvement of stakeholder s with system component σ_i in lifecycle stage γ_j. This captures how different stakeholders manage or interact with system components during various phases. In addition to stakeholder involvement, value metrics, such as cost, profit, and environmental impact, can be represented through annotations. These metrics can be computed for each phase and stakeholder involvement as follows:

$$V_{s,\lambda_j} = \sum_{m=1}^{M} v_m(s, \lambda_j) \quad (9)$$

where V_{s,λ_j} represents the total value metric (e.g., cost, profit) for stakeholder s in phase λ_j, and $v_m(s, \lambda_j)$ is the value metric contribution of microsystem m linked to stakeholder s in that phase. The integration map provides a diagnostic view, showing stakeholder involvement across the entire product lifecycle and engineering process. Highlight collaboration patterns, gaps, or bottlenecks, and offer a dynamic exploration of value chain interactions by allowing users to interact with the map to reveal detailed value contributions.

The methodology allows for flexibility in visualizing the entire system or focusing on specific workflows, lifecycle phases, or subsystems. Stakeholders can switch between high-level overviews and detailed, workflow-specific analyses. The 2-D and 3-D visualizations created in Steps 4–7 provide insights into interactions, dependencies, and value flow across the system. By integrating value metrics in Step 6 and aligning engineering phases with lifecycle stages in Step 7, the methodology supports a comprehensive and adaptable approach to RAMI 4.0 value chain analysis. This enables stakeholders to identify optimization opportunities and make informed decisions throughout the entire product lifecycle. This unified approach ensures that the methodology not only addresses the complexities of large-scale systems, but also provides actionable insights into system performance, stakeholder engagement, and value addition. It supports a thorough analysis of smart manufacturing ecosystems within the RAMI 4.0 framework.

D. SCALABILITY AND ADAPTABILITY OF THE APPROACH

The proposed methodology demonstrates both scalability and adaptability, which are critical for managing the complexities of industrial ecosystems modeled within RAMI 4.0. Each algorithm in the approach is designed to handle varying system sizes and adapt to diverse industrial use cases. Scalability is addressed at multiple levels. In Step 1, Algorithm 1 enables efficient handling of large-scale system models in formats, such as SysML and XMI, ensuring data validation against the RAMI 4.0 schema even in complex cases. To manage interaction complexity, Algorithm 4 in Step 4 uses clustering techniques, such as DSM clustering, reducing the visual complexity of microsystem interactions. This allows the system to scale without overwhelming the user with excessive visual data. In addition, Algorithm 5 in Step 5 maintains scalability in the 3-D visualizations by dynamically adjusting microsystem density, subdividing high-density clusters to preserve clarity and performance.

Adaptability is achieved through flexible mappings and workflow configurations. Algorithm 2 in Step 2 introduces customizable mapping rules, which allow users to define how microsystems are placed on the RAMI 4.0 axes, adapting the system to various industrial contexts. Furthermore, Algorithm 3 in Step 3 provides dynamic filtering and mapping of microsystems based on workflows and lifecycle phases, enabling stakeholders to analyze different system configurations without altering the core architecture.

The performance of the system can be evaluated using measurable metrics to ensure its effectiveness in real-world industrial conditions. For example, rendering time is a crucial metric, especially when visualizing complex 3-D models, such as the RAMI 4.0 cube. It is important to maintain optimal rendering speeds even with large datasets, and Algorithm 5 addresses this by dynamically adjusting the scale and density of visual elements to enhance performance.

Interactivity is another key metric, as real-time user actions, such as zooming, rotating, or filtering, are essential for an adequate user experience. Algorithms 6 and 7, in Steps 6 and 7, respectively, support interactivity by incorporating features, such as tooltips and filters, allowing users to focus on specific metrics or microsystem contributions effectively. Additional measurable aspects include data accuracy, ensuring that the visualized data accurately reflect real-time system states. The intuitiveness and accessibility of the interface for stakeholders with different technical backgrounds also play an important role in evaluating the usability of the system.

VI. ILLUSTRATIVE EXAMPLE OF MULTIDIMENSIONAL VISUALIZATIONS USING THE SHP USE CASE

This section illustrates the proposed multidimensional visualization approach by applying it to the SHP use case. The SHP value chain involves multiple stakeholders, each contributing throughout the phases of the product lifecycle, such as design, manufacturing, deployment, and maintenance. The SHP vendor (Stakeholder-1) leads the value chain, automating the manufacturing process through various microsystems, such as the smart workflow management microsystem and smart energy management microsystem. Stakeholder-2 (ECU vendor) develops the embedded control unit (ECU) and Internet of

TABLE 1. **SHP Use Case Involving Multiple Stakeholders**

SHP Life Cycle and Engineering Process Phases Execution Steps			
1	Stakeholder-3 (Final User) places an order for SHP to Stakeholder-1 (SHP vendor)	**7**	Technicians of both Stakeholder-1 and Stakeholder-2 exchange information for training and education purposes
2	Stakeholder-1 initiate the SHP manufacturing workflow and procurement processes of its parts from third parties	**8**	Stakeholder-1 procures the services of the deployment technician
3	Stakeholder-1 starts the SHP manufacturing processes and places order with the Stakeholer-2 for the Embedded Control Unit (ECU) for SHP	**9**	The deployment technician gets relevant training and education from Stakeholder-1
4	Stakeholder-1 executes the manufacturing of SHP, while Stakeholder-2 initiate its workflow process to produce the ECU	**10**	Stakeholder-3 places an order with the deployment technician for SHP deployment
5	Stakeholder-2 starts the manufacturing process of ECU	**11**	After successful deployment of SHP, Stakeholder-3 gets training and education from Stakeholder-1 on how to use and maintain the SHP
6	Stakeholder-2 executes the manufacturing process of ECU	**12**	Stakeholder-1 gets feedback from Stakeholder-3 and deployment technician to improve the design of the SHP and share relevant information with the Stakeholder-2 as well

Things (IoTs) software, enabling remote control and predictive maintenance of the SHP. The final user (Stakeholder-3) interacts with the SHP through various IoT services throughout its lifecycle. This example illustrates how visualization methodology enables stakeholders to optimize system performance by understanding the interactions and dependencies within the value chain. The SHP use case demonstrates the practical application of the visualization methodology proposed in Section V-C to a real-world scenario, aiding stakeholders in optimizing system performance and understanding value chain complexities. This use case example illustrates how the visualization approach uncovers system interactions, interdependencies, and value chain insights across lifecycle phases, ensuring clarity and applicability in diverse industrial scenarios.

Step 1—Input Specification and Preprocessing: For this step, the necessary input system model data have been provided for the entire SHP use case across all stakeholders. These data can be found in a publicly available GitHub repository[1]. After validation, the data are transformed into a structured JSON format to ensure consistency across the system and facilitate smooth integration for analysis and visualization processes. This step is critical to maintaining the integrity of the entire value chain analysis.

Step 2—Mapping Microsystems to RAMI 4.0 Axes: In this step, each microsystem in the SHP use case is mapped to RAMI 4.0's 3-D axes. The mapping of these microsystems was performed using the rule-based approach described in Algorithm 2. The JSON files from Step 1 are preprocessed and validated against the RAMI 4.0 schema, allowing for accurate and dynamic mapping.

Step 3—Dynamic Workflow and Lifecycle Phase Mapping: This step aligns the SHP lifecycle execution steps with the RAMI 4.0 microsystem mappings from Step 2. Table 1 summarizes the interactions and steps taken by each stakeholders during the engineering and operational lifecycle of the SHP. This step ensures that the activities of each stakeholder are correctly assigned to the relevant phases of the lifecycle, providing a structured view of how the engineering and operational workflows progress over time.

Step 4—System-of-Microsystems Interaction Matrix: The system-of-microsystems interaction matrix, as illustrated in Fig. 2, visualizes the interactions among IT/OT microsystems across lifecycle phases in the SHP use case. Diagonal elements represent lifecycle phase involvement, whereas off-diagonal elements highlight cross-phase interdependencies. The clustering techniques applied in Algorithm 4 reduce visual clutter by grouping highly interdependent microsystems, providing actionable insights into hidden complexities. For example, the interactions between the smart workflow management microsystem and the smart energy management microsystem reveal energy dependencies influencing production workflows. This visualization captures both intra and interstakeholder interactions, enabling stakeholders to identify bottlenecks, optimize workflows, and enhance coordination.

Each cell in the matrix represents an interaction between two microsystems, with diagonal cells highlighting the engineering process phases in which a microsystem is actively involved. Color-coding is used to differentiate stakeholders, allowing quick identification of responsibility for specific interactions. For example, interactions between the SHP vendor's smart workflow management microsystem and the ECU vendor's ECU reveal key collaborative processes necessary for SHP production and deployment.

This matrix illustrates the approach described in Algorithm 4. It helps stakeholders identify inefficiencies, risks, and bottlenecks in the value chain. Highly interdependent microsystems, especially those from the same stakeholder, can be optimized or consolidated on the basis of their interactions. Visualization also reveals unintended consequences of changes in one microsystem, ensuring proper coordination across the system. This visualization supports the use of

[1] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/blob/main/algorithms-input-output-files/SHP-SystemModel

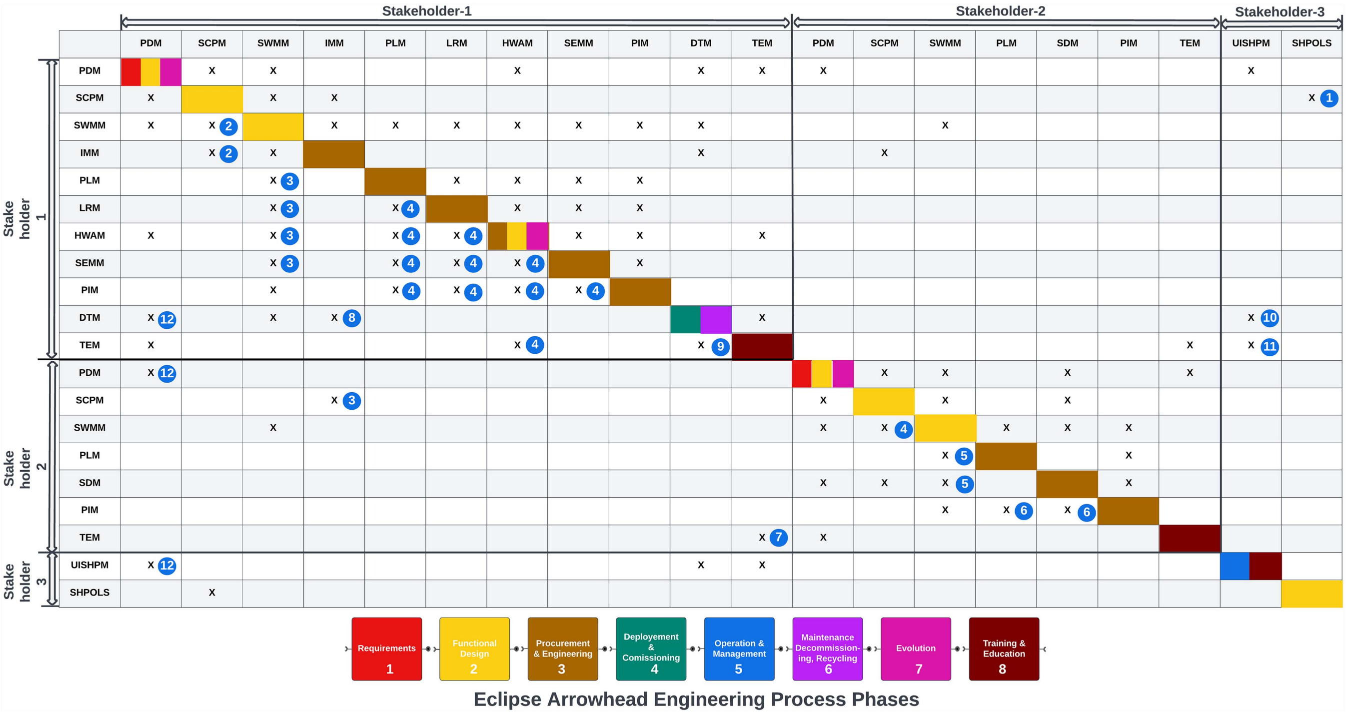

FIGURE 2. **System-of-microsystems interaction matrix and its mapping with the engineering process phases of the product (SHP) entire life cycle, where PDM: product design microsystem, SCPM: smart contract proxy microsystem, SWMM: smart workflow management microsystem, IMM: inventory management microsystem, PLM: production line microsystem, LRM: logistic robot microsystem, HWAM: human/worker aide microsystem, SEMM: smart energy management microsystem, PIM: production information microsystem, DTM: deployment technician microsystem, TEM: training and education microsystem, SDM: software development microsystem, UISHPM: user interface and SHP management microsystem, and SHPOLS: SHP ordering legacy system.**

clustering techniques with a DSM approach based on interaction density and reorganization of microsystems in the interaction matrix, grouping highly interactive microsystems within the same RAMI 4.0 cube [37], [38], [39].

The SHP use case exemplifies how the interaction matrix manages the complexity of a smart manufacturing ecosystem. The matrix traces the interactions as described in Table 1, allowing stakeholders to link processes, such as SHP production (Stakeholder-1) with ECU development (Stakeholder-2). It provides a high-level overview of dependencies throughout the engineering process and product lifecycle, supporting risk. In general, the interaction matrix is a key tool for aligning engineering processes with value chain analysis, enabling workflow optimization, reducing risks, and improving system performance.

Step 5—3-D Visualization of Microsystems in Stakeholder RAMI 4.0 Cubes: The 3-D visualization of microsystems in RAMI 4.0 cubes, as illustrated in Fig. 3, offers an intuitive representation of how IT/OT microsystems are mapped within the RAMI 4.0 solution space for the SHP use case. This visualization highlights the allocation of microsystems between different layers and stakeholders, facilitating a comprehensive analysis of the SHP value chain, its engineering processes, and its lifecycle phases. Fig. 3 illustrates the approach described in Algorithm 5; the visualization generates RAMI 4.0 cubes for each stakeholder, encapsulating their respective microsystems as ellipsoids. These ellipsoids represent roles, services, and interactions within the three axes of RAMI 4.0, ensuring accurate mapping of each microsystem's functional and technical characteristics. This modular approach helps define technical and operational boundaries, improving the clarity of system structure.

Each microsystem encapsulates specific microservices, adhering to the principles of loose coupling and high cohesion, which enhance modularity, maintainability, and scalability. The administrative shells and technical assets are represented within the appropriate layers, ensuring the mapping of both functional and communication properties across the RAMI 4.0. The 3-D visualization also supports the integration of legacy IoT systems with newer I4.0 technologies, treating legacy systems, such as the SHP ordering system as "closed system" within the RAMI 4.0 cubes. This ensures interoperability while maintaining architectural flexibility. It also accounts for the inclusion of intermediate layers using visual markers, such as orange circles, as described in Algorithm 5. For example, the production line microsystem is mapped on the asset, integration (intermediate), and communication layers simultaneously. This is highlighted in Fig. 3, where orange circles mark the intersection points of ellipsoids with the intermediate layers, indicating which architectural layers are included. In addition, the endpoints of the ellipsoid's major axis convey further information: for example, the

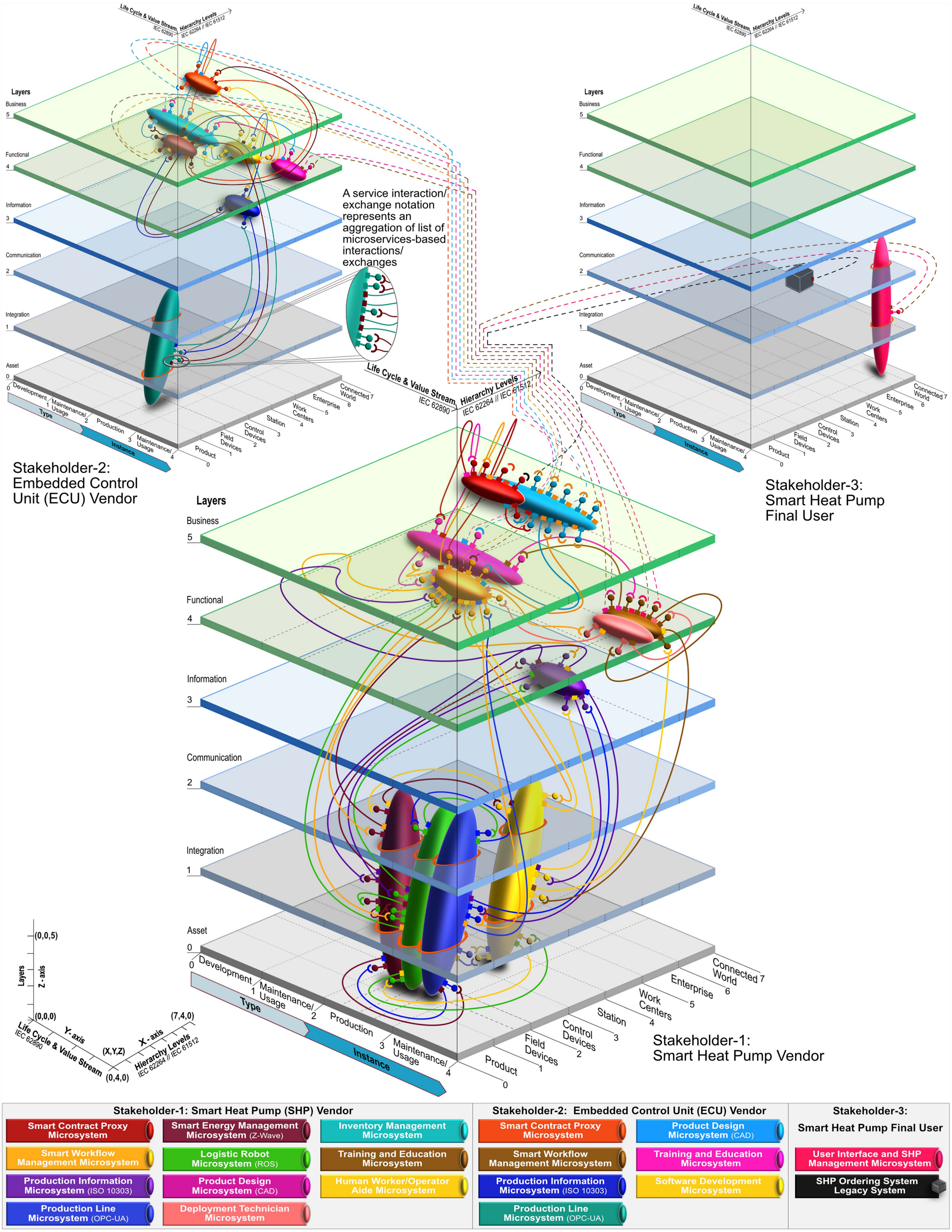

FIGURE 3. RAMI 4.0 value chain visualization adapted to the SHP use case.

vertical ellipsoid representing Stakeholder-2's production line microsystem starts at the asset layer and ends just below the information layer, meaning it includes the asset, integration, and communication layers. The position and endpoint below the information layer signify that this layer is not included. Along the vertical axis of the RAMI 4.0 cube, each ellipsoid is placed on the layers it belongs to and extends just above the last layer it represents. This concept is detailed in Algorithm 5 of Step 5 of the methodology in Section V.

Another key feature of this visualization is the service interaction/exchange notation, encapsulating the microservice interaction tuple as explained in Section V-B, which shows the flow of service-based data between microsystems and stakeholders, such as the interaction between Stakeholder-1's production line microsystem and Stakeholder-2's systems. This allows stakeholders to clearly see how service-based information flows throughout the SHP lifecycle. Furthermore, color-coded ellipsoids and interaction lines improve decision-making by highlighting stakeholder contributions and identifying bottlenecks, dependencies, and opportunities for optimization within the SHP value chain. By offering a comprehensive view, the 3-D visualization enables stakeholders to make informed decisions regarding cost, functionality, and performance, as seen with key components, such as smart energy management and human/worker operator aide microsystems.

In general, this 3-D visualization demonstrates how mapping of microsystems ellipsoids within RAMI 4.0 using the proposed visualization approach described in Algorithm 5 offers a scalable and flexible solution to manage and optimize smart industry ecosystems. It supports and improves decision-making by offering a clear and comprehensive view of interactions and dependencies across multiple stakeholders.

Step 6—RAMI 4.0 Value Addition Projection: The RAMI 4.0 value addition projection provides a comprehensive view of how value is generated and distributed between stakeholders within a smart industry ecosystem, focusing on the use case of SHP. It incorporates metrics, such as cost flows, profit margins, energy consumption, and environmental impacts, enabling stakeholders to make informed decisions regarding cost-efficiency and sustainability throughout the product lifecycle.

Figs. 4 and 5 illustrate how using Algorithm 6, the visualization computes and displays the cost and value contributions of each microsystem and stakeholder. By mapping these metrics onto the RAMI 4.0 hierarchy plane, the projection highlights interconnections between assets and microsystems, offering insights into stakeholder contributions across different levels of the system architecture. This approach, following the ISA-95 model, captures both organizational and physical aspects of the system. The projection reveals how costs and value flow through the product lifecycle, from design to production and maintenance. For example, both the SHP and ECU vendors contribute at different stages, and their contributions are mapped precisely, as shown in Figs. 4 and 5.

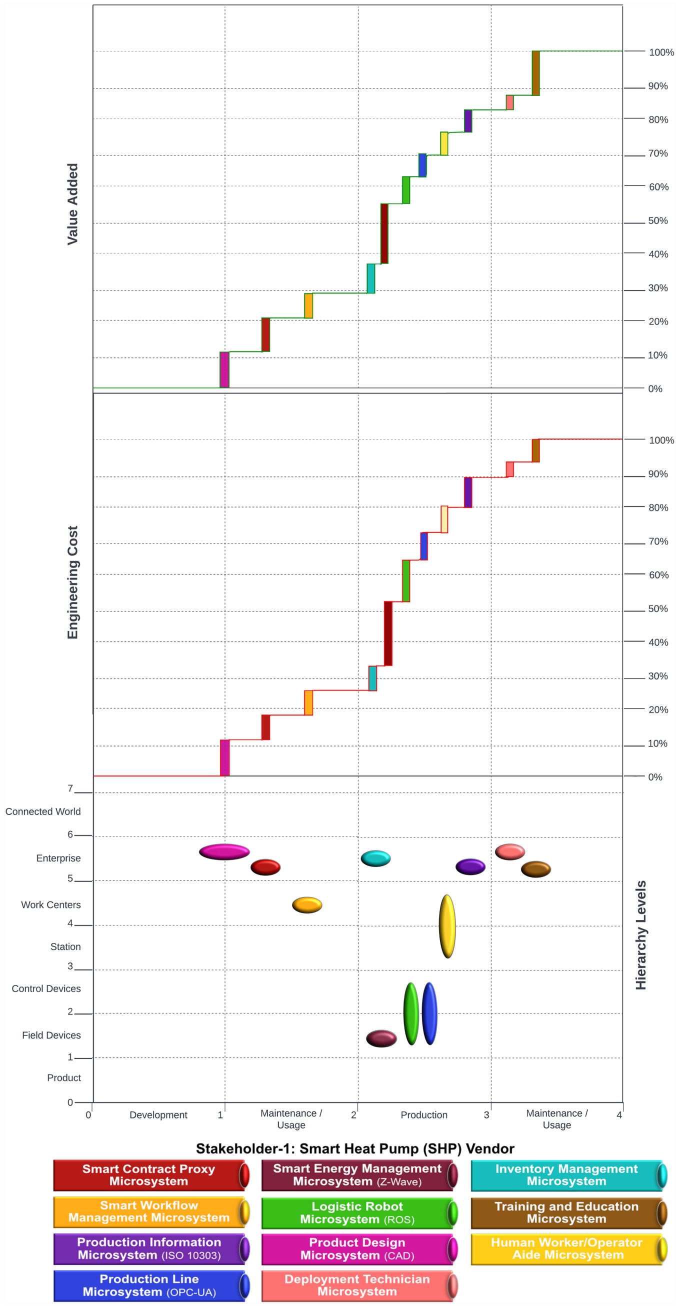

FIGURE 4. Microsystems cost and value addition projections of Stakeholder-1 of the SHP use case.

This projection is particularly effective for identifying interdependencies between stakeholders and microsystems, highlighting opportunities for cost reduction and value maximization. It shows how costs incurred by one stakeholder translate into value for another. For example, investments in advanced automation, such as in the smart workflow management and human/worker aide microsystems, can reduce operational costs while enhancing overall value. In addition, the value addition projection allows for comparative analysis across RAMI 4.0 layers, mapping costs, and value throughout the hierarchy and lifecycle axes. This analysis helps

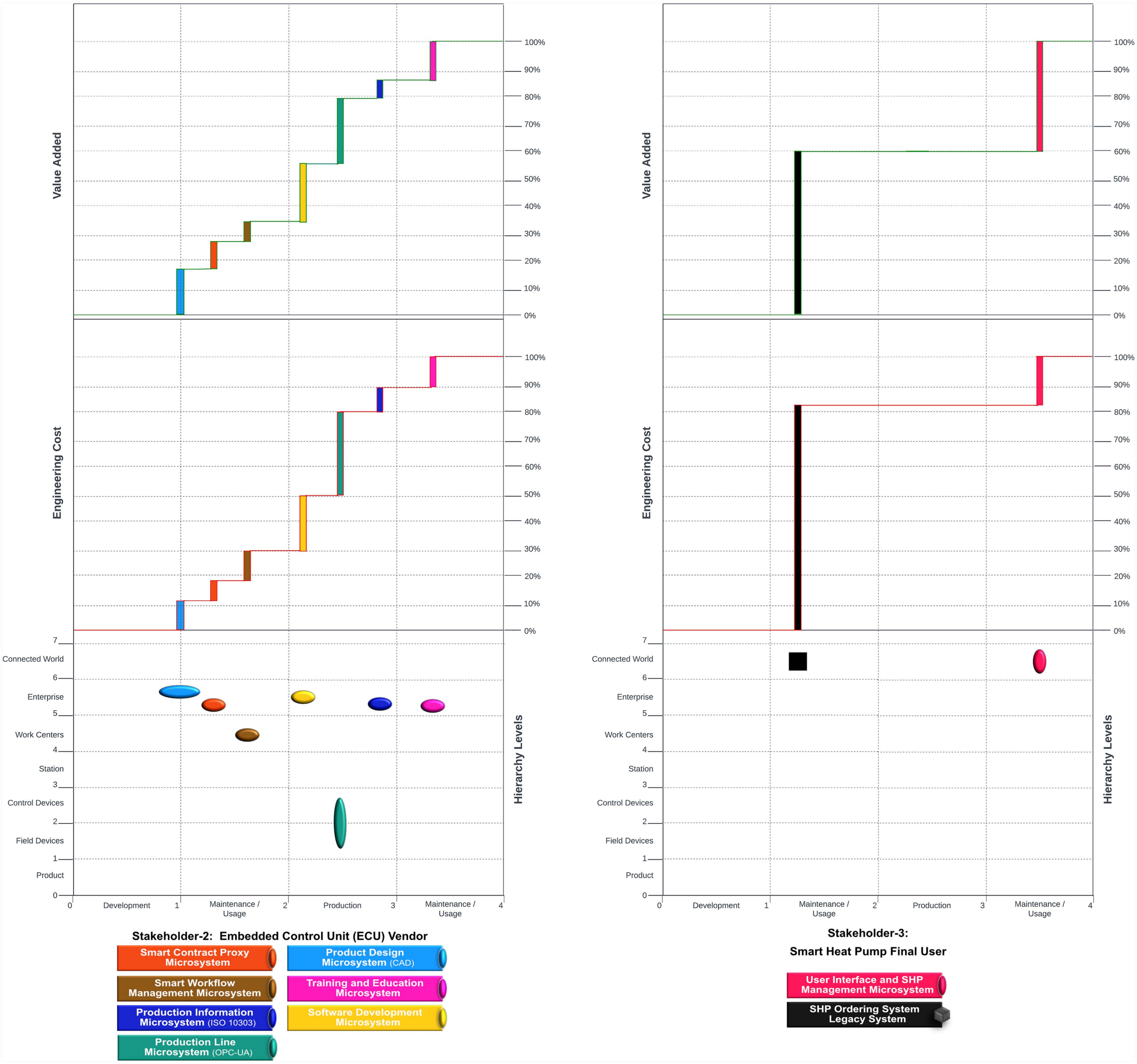

FIGURE 5. **Microsystems cost and value addition projections of Stakeholder-2 and Stakeholder-3 of the SHP use case.**

stakeholders assess profitability, process efficiency, and alignment with long-term objectives. The flexibility of the projection also enables the incorporation of sustainability metrics, such as energy consumption and carbon footprint, crucial in today's eco-conscious industrial environment. This visualization provides stakeholders with valuable insights into cost and value distribution within the ecosystem, facilitating the coordination between engineering and business processes to optimize smart manufacturing systems.

Step 7—Engineering Process Phases and Product Life Cycle Integration Map: This step presents the integration map aligning the product life cycle with the corresponding engineering process phases based on RAMI 4.0, as illustrated in Fig. 6 and described in Algorithm 7. The visualization focuses on the phases of the engineering process, supply chains, and stakeholder interactions throughout the product life cycle. It is structured around eight phases developed by Urgese et al. [42]. This mapping improves the applicability of RAMI 4.0 by emphasizing the dynamics of the value chain, the relationships between the engineering phases, and the synergies between stakeholders and system components. The map is organized into columns representing engineering phases and rows showing different aspects of the value chain. Stakeholders are color-coded with unique IDs, providing a clear view of their roles. Fig. 3 demonstrates the multistakeholder SHP use case.

The visualization covers four distinct aspects: the product life cycle, engineering phases, the value and supply

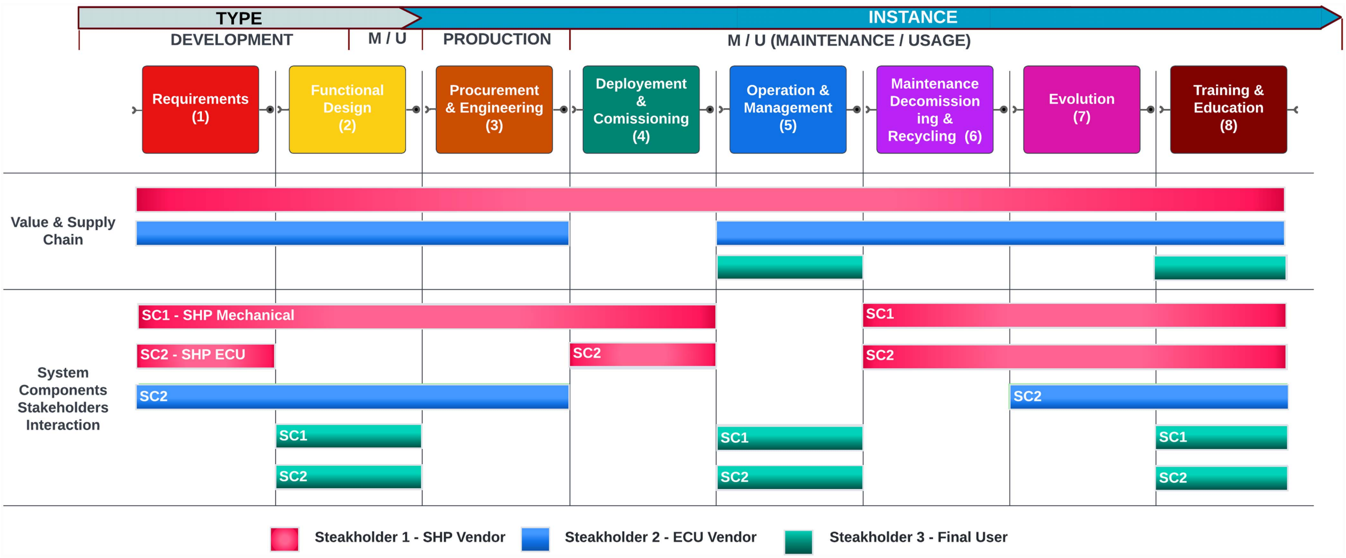

FIGURE 6. **Engineering process phases and product life cycle integration map view of RAMI 4.0. The mapping of engineering process phases, value and supply chain, and stakeholder interaction throughout the life cycle of the product (SHP).**

chain, and stakeholder interaction. For example, it shows that Stakeholder-1 is involved in all phases of the SHP's life cycle, while the SHP mechanical (SC1) and SHP ECU (SC2) components highlight collaboration between Stakeholder-1 and Stakeholder-2. It also specifies that the ECU, developed by Stakeholder-2, is deployed by Stakeholder-1, and Stakeholder-3 is engaged in the operation and management, and training and education phases.

This visualization offers insights not explicitly available in RAMI 4.0, revealing the involvement of stakeholders in each life cycle stage and helping to identify opportunities for process optimization. By examining stakeholder participation, organizations can detect inefficiencies or cost reduction opportunities, thus improving decision-making and understanding of value chain interactions and responsibilities.

Results: This SHP use case example illustrates how our approach enables detailed value chain analysis within the RAMI 4.0 framework. The multidimensional visualizations effectively reveal microsystem interactions, stakeholder contributions, and value flows across various phases of the SHP life cycle and engineering processes, providing comprehensive insights into the system's operational and structural dynamics.

In addition, Table 2 provides a detailed overview of the SHP use case, linking each algorithm to its inputs, outputs, insights, and visualizations. It illustrates the progression of the methodology from preprocessing to interaction clustering and multidimensional visualization, highlighting specific figures generated at each step, such as the interaction matrix (see Fig. 2) and value projections (see Figs. 4 and 5). It also demonstrates how the proposed algorithms uncover dependencies, optimize workflows, and enable value chain analysis in smart manufacturing systems. By focusing on the SHP use case as an illustrative example, it showcases the practical application of the visualization approach, helping stakeholders understand how the methodology supports decision-making across lifecycle phases.

The 3-D visualization of RAMI 4.0 cubes illustrates how microsystems are distributed across business, functional, and asset layers, clarifying the roles of stakeholders and the flow of communication between technical and business processes. It also facilitates the integration of legacy and modern I4.0 systems, ensuring interoperability and scalability within the ecosystem. The system-of-microsystems interaction matrix maps relationships between microsystems across stakeholders, providing a clear view of engineering phases and identifying inefficiencies, risks, and optimization opportunities. This ensures well-coordinated system changes.

The value addition projections offer quantitative insights into cost flows and profit margins, helping stakeholders assess profitability, reduce costs, and improve value throughout the SHP life cycle. The engineering process and the life cycle integration map improve collaboration by highlighting stakeholder contributions at each phase, clarifying roles, and reducing redundancies. In summary, integration of these visualizations enables a comprehensive evaluation of the SHP ecosystem, driving improvements in efficiency, cost management, and stakeholder collaboration. These results underscore the value of RAMI 4.0-based analysis in creating adaptable and scalable smart manufacturing ecosystems.

VII. PROOF-OF-CONCEPT IMPLEMENTATION

To illustrate the practical application of the proposed visualization approach, we are developing a web-based interactive proof-of-concept tool available online at GitHub repository. The tool is implemented using Python, offering a 360° view of the use case and the associated value chain throughout the system life cycle. It supports visualization of microsystem

TABLE 2. Application of the Proposed Methodology Steps and Algorithms to the SHP Use Case

Metho-dology	Input	Output	Key Insights Revealing Hidden Complexities	Visual-ization	Algo-rithm
Step 1:	SHP system model data in DSL (e.g., SysML/ XMI format)	Validated and transformed JSON data	Ensures uniformity in the data schema across all stakeholders of SHP Use Case, avoiding errors during subsequent mappings and visualizations.	N/A	Alg1[2]
Step 2:	Preprocessed JSON data	Microsystems mapped to RAMI4.0 axes (e.g., Smart Workflow Management Microsystem on Worker Centers Level, Maintenance (Type) Lifecycle Phase, and Functional Layer)	Enabling stakeholders to analyze lifecycle and hierarchical relationships dynamically. Identifies overlapping lifecycle phases, such as HWAM functioning in both production and maintenance stages.	N/A	Alg2[3]
Step 3:	SHP lifecycle workflows, services and engineering process steps	Filtered microsystems mapped to workflows (e.g., Smart Workflow Management Microsystem focusing on production workflows)	Focuses on relevant microsystems for workflows, e.g., filtering Smart Workflow Management Microsystem and Inventory Management Microsystem interactions during SHP production workflows. Highlights redundancies in production, revealing inefficiencies in Stakeholders 1 and 2 collaboration.	N/A	Alg3[4]
Step 4:	Interaction data rom SHP	Clustered interaction matrix revealing dependencies (e.g., between Smart Workflow Management Microsystem & Smart Energy Management Microsystem)	Shows how Smart Energy Management Microsystem delays disrupt Smart Workflow Management Microsystem workflows, identifying bottlenecks and interdependencies.	Fig. 2	Alg4[5]
Step 5:	Clustered microsystems from Algorithm 4	RAMI4.0 cubes visualizing SHP microsystem roles, services, and dependencies	Minimizes visual clutter by grouping interdependent microsystems into stakeholder -specific RAMI cubes.	Fig. 3	Alg5[6]
Step 6:	Cost and value data for SHP microsystems	RAMI4.0 planes showing cost-to-value mappings for each microsystem	Reveals inefficiencies where Human Worker Aide Microsystem incurs high costs but adds limited value.	Fig. 4 Fig. 5	Alg6[7]
Step 7:	Stakeholder roles and engineering phases	2D integration map aligning lifecycle phases with stakeholder contributions	Exposes collaboration gaps between Stakeholders 2 and 3, particularly during deployment and training phases.	Fig. 6	Alg7[8]

interaction within the RAMI 4.0 cube, with the potential to provide information on stakeholder contributions, process optimizations, and the distribution of value addition.

The ongoing development of the tool, as illustrated in Fig. 7, shows the preliminary 3-D visualization of microsystem interactions in the RAMI 4.0 solution space. The tool enables users to interact and explore multiple dimensions of the system, including lifecycle stages, hierarchy levels, and architecture layers. It provides the basis for interactivity in the 3-D visualization of microsystems. For example, ellipsoidal representations of microsystems can encapsulate detailed information, such as cost, value, and relevant documentation. In addition, the service interaction/exchange notation can dynamically provide essential data on microservice costs, endpoints, orchestration, and authorization rules, making the visualization both informative and interactive. This level of interactivity will enable stakeholders to engage directly with the visualized microsystems, facilitating more comprehensive analysis and decision-making in real time. It is designed to improve understanding of how microsystems exchange data and perform within smart manufacturing ecosystems. The proof-of-concept is hosted on GitHub repository,[9] and all sample input, output, and configuration files required for each step of the visualization approach are available in the repository[10]. These files are essential for configuring smart manufacturing ecosystems using RAMI 4.0 and can be adapted for various industrial scenarios. The proof of concept, as a work in progress, demonstrates the potential to integrate RAMI 4.0-based value chain visualizations into smart manufacturing workflows.

[2] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/95ba8ba4c6809bc4c48bd18260a828cf792e1697/alg1

[3] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/95ba8ba4c6809bc4c48bd18260a828cf792e1697/alg2

[4] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/95ba8ba4c6809bc4c48bd18260a828cf792e1697/alg3

[5] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/95ba8ba4c6809bc4c48bd18260a828cf792e1697/alg4

[6] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/95ba8ba4c6809bc4c48bd18260a828cf792e1697/alg5

[7] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/95ba8ba4c6809bc4c48bd18260a828cf792e1697/alg6

[8] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/95ba8ba4c6809bc4c48bd18260a828cf792e1697/alg7

[9] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ

[10] [Online]. Available: https://github.com/javedsalman/RAMI4.0-VIZ/tree/main/algorithms-input-output-files

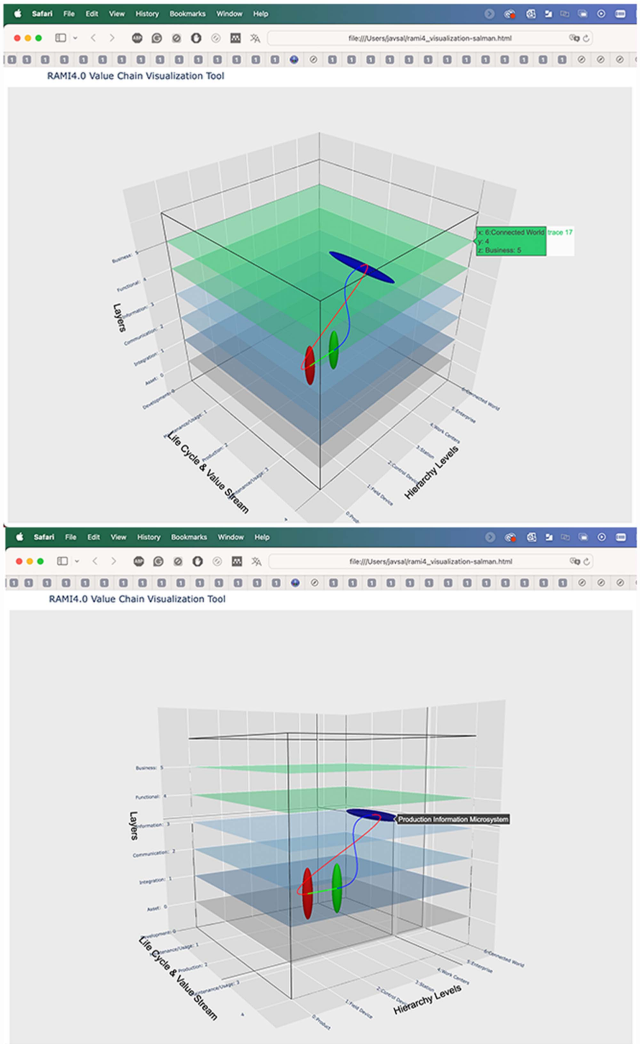

FIGURE 7. Proof-of-concept, as a work in progress, exemplifies the potential of integrating RAMI 4.0-based value chain visualizations.

VIII. DISCUSSION

This section highlights the strengths and implications of the proposed methodology, which enables value chain analysis within the RAMI 4.0 framework. By offering multidimensional insights into microsystem interactions, stakeholder contributions, and engineering process phases, our approach bridges the gaps identified in Section IV between theoretical frameworks and practical real-world industrial applications. A key strength of this methodology lies in its ability to support navigating the complexities of the RAMI 4.0 3-D model, enabling it to fulfill major requirements for engineering the digitalization of industrial value streams and the life cycles of industrial cyber-physical systems. This contributes significantly to the growth and success of smart industrial ecosystems by facilitating informed decision-making, efficient resource allocation, and comprehensive value chain analysis at runtime.

The visualizations presented allow stakeholders to gain a clearer understanding of the interactions between various components, identify risks, and uncover optimization opportunities. For example, visualizing the strong interdependence between microsystems could reveal areas where consolidating them would simplify the system's design. In addition, visualizing these interactions helps predict the cascading effects that changes in one microsystem may have on others. This ensures that system-wide changes are well coordinated and their potential impacts understood, reducing the risk of unintended disruptions.

These visualizations not only help transition to I4.0 by evaluating microsystem costs and value contributions, but also form the foundational framework for future tools that focus on value chain analysis in smart manufacturing ecosystems. However, there remains a need to integrate these visualizations with real-time production processes through workflow management systems. This integration would allow for continuous value chain analysis during operational and maintenance phases, enhancing decision-making capabilities at runtime.

Furthermore, the 3-D visualization of microsystems allows for interactive representations, which can provide detailed information on costs, value-addition, and documentation as explained in Section VII. The service interaction/exchange notation can offer essential data on microservice costs, endpoints, orchestration, and authorization rules, enabling stakeholders to engage directly for real-time analysis and decision-making. In addition, the 3-D visualization approach could be adapted to align with the RAMI 5.0 framework [43]. RAMI 5.0 emphasizes human-centric approaches, sustainability, and mass personalization. Our visualization approach could extend beyond IT/OT interactions to include human–machine collaboration, energy consumption, and sustainability metrics. This adaptation would allow stakeholders to visualize human involvement alongside energy and sustainability impacts, which aligns with RAMI 5.0's goals of balancing technological innovation with human-centric operations and environmental considerations.

These visualizations can also provide end-to-end traceability and historical data mapping, which can facilitate the control system application. Using cost accounting and management techniques, one can further improve value chain analysis [44]. This approach supports cost accounting and management techniques that assign costs to specific microsystem activities, enabling stakeholders to evaluate performance across the value chain [45]. This further facilitates operational and financial optimization in complex, multi-stakeholder environments. Future work could focus on developing methodologies for cost accounting in microservice-based RAMI 4.0 solutions, particularly within I4.0 environments where the integration of advanced automation and evolving manufacturing processes is crucial.

In summary, the proposed visualizations serve as a comprehensive approach for analyzing value chains in smart manufacturing ecosystems. They support the identification of bottlenecks, operational inefficiencies, and collaborative opportunities, while laying the groundwork for future integration with frameworks, such as RAMI 5.0.

IX. CONCLUSION

The proposed visualization approach for RAMI 4.0-based value chain analysis effectively enables the integration of IT/OT systems in smart manufacturing ecosystems. By leveraging tools, such as the *engineering process phases and product life cycle integration map*, *system-of-microsystems integration matrix*, and *RAMI 4.0 value addition projection*, organizations can maximize their existing infrastructure while transitioning to advanced technologies, leading to reduced costs and minimal operational disruptions.

This methodology addresses the complexities of managing and visualizing interactions between IT/OT microsystems and value chains within multistakeholder environments. It offers a comprehensive understanding of the interconnections between product life cycles, engineering phases, and organizational processes. The multidimensional visualization techniques presented help stakeholders analyze these interactions from both operational and strategic perspectives, providing clear insights into the relationships between production, engineering, and business processes. A key strength of the approach is its modularity, scalability, and flexibility, ensuring that it can adapt to evolving technologies and market conditions. The methodology also supports informed decision-making and facilitates efficient resource allocation at run-time, ultimately contributing to the growth and success of smart industry ecosystems.

In conclusion, these visualization approaches are particularly valuable for organizations seeking to optimize their value chains and transition smoothly to I4.0. They enable effective collaboration among stakeholders, enhance system performance, and provide a clearer path toward achieving operational excellence in a dynamic industrial landscape.

FUTURE WORK

Future work in advancing the understanding and application of value chain analysis and costing mechanisms within the RAMI 4.0 solution space offers several promising directions. First, integrating cost accounting and management techniques into RAMI 4.0 could significantly enhance value chain analysis, performance improvement, and cost reduction in smart industry ecosystems. Leveraging frameworks, such as Arrowhead, with their dynamic orchestration and microservice interoperability, facilitates a comprehensive understanding of resource consumption and value addition throughout the RAMI 4.0 solution space.

Second, conducting value chain analysis case studies in real-world scenarios would offer valuable insights into the practical implementation of RAMI 4.0, shedding light on its effectiveness and potential challenges. By examining the experiences of organizations adopting RAMI 4.0, researchers can refine the model and develop best practices for implementation, thus ensuring its successful integration into diverse industrial contexts. In addition, investigating RAMI 4.0's impact on organizational performance, including productivity, efficiency, and competitiveness, would provide valuable insights for informed decision-making regarding its adoption or similar reference architecture models. This holistic approach to research and development ensures that RAMI 4.0 remains relevant and adaptable to the evolving industrial landscape, contributing to the ongoing optimization of smart industry ecosystems in the era of I4.0 and future industrial innovations.

APPENDIX A ALGORITHMS

This appendix includes all the algorithms that implement each step of the proposed multidimensional value chain analysis described in Section V.

Algorithm 1: Input Specification and Preprocessing: Algorithm 1 outlines the process of transforming system model data, provided in DSL using format, such as SysML or XMI, into a structured JSON format. This algorithm ensures that the input data adhere to the RAMI 4.0 schema, validating and enriching it with all necessary attributes before it can be used in subsequent steps of the methodology.

Algorithm 2: Mapping Microsystems to RAMI 4.0 Axes: Algorithm 2 presents the process of mapping microsystems to the RAMI 4.0 cube's three axes: hierarchy levels (X-axis), lifecycle stages (Y-axis), and architecture layers (Z-axis). The algorithm utilizes a rule-based approach to determine the appropriate coordinates for each microsystem, ensuring accurate representation within the RAMI 4.0 framework. It offers flexibility through predefined rules and user-defined inputs, allowing for dynamic updates to the mapping configuration.

Algorithm 3: Dynamic Workflow and Lifecycle Phase of Use Case Mapping: Algorithm 3 focuses on aligning specific use cases and workflows with the mapped RAMI 4.0 microsystems and interactions. By filtering out unnecessary data and focusing on relevant microsystems and services for a particular workflow or lifecycle phase, this algorithm enables more focused analysis. The final output is a filtered dataset that supports use case-specific visualizations for stakeholders, providing clearer insights into dynamic system behavior.

Algorithm 4: System-of-Microsystems Interaction Matrix with Clustering and Phase Assignment: Algorithm 4 constructs an interaction matrix that captures the interactions between microsystems, along with their corresponding engineering phase assignments. This matrix visualizes the dependencies between microsystems and identifies key clusters based on interaction density using a DSM approach. The algorithm supports both complete system architectures and specific workflow visualizations, facilitating the understanding of interdependencies and helping to identify optimization opportunities within the system.

Algorithm 1: Input Specification and Preprocessing.

Inputs:
System Model file F in DSL format (e.g., SysML, XMI) and *rami_schema.xsd*
Outputs:
Structured and validated data for RAMI 4.0 mapping *json_data*

function PREPROCESSINPUT (F)
Step 1: Load and Parse Input
    Load the input file F and extract relevant data (microsystems, interactions)
Step 2: Validate Against RAMI 4.0 Schema
    Validate the extracted data using *rami_schema.xsd*
    if Validation Fails **then**
        Prompt user to correct the input data
        return Error
    end if
Step 3: Convert Data to JSON Format
    Transform the parsed data into the structured JSON format for further processing
Step 4: Enrich and Validate JSON Data
    Ensure that the microsystem and interaction data are complete and conform to the required fields
Step 5: Finalize JSON Data
    return the structured and enriched *json_data* for RAMI 4.0 mapping
end Function

Algorithm 2: Mapping of Microsystems to RAMI 4.0 Axes.

Inputs:
Validated data *json_data* ▷Input after preprocessing
Rule-based mapping configuration *mapping_config* ▷Rules for mapping to RAMI 4.0 axes
Outputs:
Mapped microsystem data *system_mapped_data* ▷Microsystem coordinates in RAMI 4.0 (X, Y, Z)

function MAPTORAMI4AXES (*json_data*, *mapping_config*)
Step 1: Load Configuration
    Extract mapping rules from configuration
Step 2: Map Microsystems to RAMI 4.0 Axes
    for all $microsystem \in json\_data.microsystems$ **do**
        Retrieve relevant attributes for mapping: *type*, *role*, *services*, *shell*
Step 2.1: Map to X-Axis (Hierarchy Level)
    Apply the mapping rule for the X-axis based on the microsystem's *type* and *role*:

$$X_m = f_x(\text{microsystem.type, microsystem.role}, \psi_{\text{hierarchy}})$$

    where $\psi_{\text{hierarchy}}$ is the set of rules for hierarchy mapping.
    if no rule matches **then**
        Prompt the user for input and incorporate it into the rule set:

$$X_m = \begin{cases} \psi_{\text{hierarchy}}(a, b) & \text{if match found,} \\ \text{PromptUserForMapping}(a, b) & \text{if no match found.} \end{cases}$$

    end if
Step 2.2: Map to Y-Axis (Lifecycle Stage)
    Apply the lifecycle rule based on provided/consumed services similarly:

$$Y_m = f_y(\text{microsystem.provides, microsystem.consumes}, \psi_{\text{lifecycle}})$$

    If no match is found, prompt the user to provide a mapping for the Y-axis.

Step 2.3: Map to Z-Axis (Architecture Layer)

Apply the rule for Z-axis based on the *shell* attribute:

$$Z_m = f_z(\text{microsystem.shell}, \psi_{\text{layers}})$$

If no match is found, prompt the user for input.

Assign coordinates $microsystem.coordinates \leftarrow (X_m, Y_m, Z_m)$

end for

Step 3: Return Mapped Data

return $system\_mapped\_data$ with coordinates mapped for each microsystem

end Function

Algorithm 3: Dynamic Integration of Workflow and Lifecycle of Use Case.

Inputs:

Mapped system data $system\_mapped\_data$ from previous step

Set of possible workflows $available\_workflows$

Workflow data $workflow\_data$ with services S_w or Product Lifecyle Execution Steps as in Table 1

Outputs:

Filtered data $usecase\_mapped\_data$ ▷Filtered data relevant to the selected workflow or lifecycle stage

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Step 1: User Selection of Workflow

Present available workflows to the user

$selected\_workflow \leftarrow$ User-selected workflow from $available\_workflows$

Retrieve corresponding workflow data $workflow\_data$

function FILTERDYNAMICWORKFLOW ($system\_mapped\_data$, $workflow\_data$)

Step 2: Initialize Filtered Data Structure

Initialize empty $usecase\_mapped\_data$ for storing relevant microsystems and interactions

Step 3: Analyze Workflow Data

for all $step \in workflow\_data$ **do**

Extract $step\_id$, $services$, and $interactions$

Step 4: Filter Microsystems by Services

$M_w \leftarrow \{m \in system\_mapped\_data.microsystems \mid m.provides \cap S_w \neq \emptyset \vee m.consumes \cap S_w \neq \emptyset\}$ ▷Filter microsystems based on services provided or consumed in this step

Add M_w to $usecase\_mapped\_data.microsystems$

Step 5: Filter Interactions

for all $interaction \in interactions$ **do**

Retrieve interacting microsystems $source\_id$, $target\_id$

if $source\_id, target\_id \in M_w$ **then**

Add $interaction$ and sequence details to $usecase\_mapped\_data$

end if

end for

end for

Step 6: Validate Interaction Mapping

for all $interaction \in system\_mapped\_data.interactions$ **do**

if $interaction$ involves microsystems in $usecase\_mapped\_data$ **then**

Add $interaction$ to the filtered data

end if

end for

Step 7: Finalize Filtered Data

Generate the final $usecase\_mapped\_data$ with microsystems and interactions specific to the workflow

return $usecase\_mapped\_data$

end Function

Algorithm 4: System-of-Microsystems Interaction Matrix With Clustering and Phase Assignment.

Inputs:
Mapped system data $system\_mapped\_data$ from earlier steps
Usecase mapped data $usecase\_mapped\_data$
Engineering phases $P = \{p_1, p_2, \ldots, p_k\}$, Workflow details W
Outputs:
Interaction Matrix A with clusters and phases assigned

function CREATEINTERACTIONMATRIXWITHCLUSTERING ($system\_mapped\_data$, $usecase\_mapped\_data$, P, W)
Step 1: Select Data for Matrix
    User chooses to visualize either the full system architecture or a specific workflow
    $M \leftarrow$ Corresponding data based on the selection
Step 2: Initialize Interaction Matrix
    Define interaction matrix A of size $n \times n$ where $n = |M|$
Step 3: Populate Matrix with Interactions
    for all microsystems $m_i, m_j \in M$ **do**
        if an interaction exists between m_i and m_j **then**
            Mark the interaction in $A[i, j]$
            if visualizing workflow **then**
                Include sequence details in $A[i, j]$
            end if
        else
            Set $A[i, j] = 0$ or leave blank
        end if
    end for
Step 4: Workflow Execution (For Use Cases)
    if visualizing workflow **then**
        for all steps in W **do**
            Map sequential and parallel execution in the matrix
        end for
    end if
Step 5: Assign Engineering Phases to Microsystems
    for all microsystem $m_i \in M$ **do**
        Identify phases P_i related to m_i
        Mark phase involvement in diagonal cells of A
    end for
Step 6: Clustering
    Calculate interaction density and apply clustering algorithms to group microsystems
    Assign each microsystem to a cluster based on interaction patterns
Step 7: Visualize the Matrix
    Construct a graphical view of A, marking interactions and phases with distinct indicators
Step 8: Display and Analyze the Matrix
    Render the matrix with cluster representation
    Identify key insights such as interdependent clusters or isolated microsystems
    return A, updated M with clusters and phases
end Function

Algorithm 5: 3-D Visualization Microsystems in Stakeholder RAMI 4.0 Cubes: Algorithm 5 provides a 3-D visualization of the RAMI 4.0 cube, representing microsystems as ellipsoids or closed system. It supports clustering-based stakeholder cubes and enhances functionality with dynamic features, such as scaling and filtering. This allows for the detailed visual analysis of the spatial relationships and interactions between microsystems within the RAMI 4.0 architecture.

Algorithm 6: RAMI 4.0 Value Addition Projection with Metrics: Algorithm 6 provides the methodology for visualizing the value addition of microsystems within the RAMI 4.0 framework. It maps key metrics, such as cost, profit, and environmental impact to the 2-D projection planes of the

Algorithm 5: 3-D Visualization of Microsystems in Stakeholder RAMI 4.0 Cubes.

Inputs:

System mapped data $system\_mapped\_data$ from previous steps
Usecase mapped data $usecase\_mapped\_data$
RAMI 4.0 cube visualization configuration $visual\_config.json$
Interaction Matrix I, Clustering threshold τ, Spatial threshold δ

Outputs:

3D visualization of RAMI 4.0 cubes with stakeholder, clusters, interactions, and dynamic insights

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function VISUALIZE3DCUBE ($system\_mapped\_data$, $usecase\_mapped\_data$, I, τ, δ)

Step 1: Select Data for Visualization

User chooses either complete system architecture or specific workflow
Set $M \leftarrow$ Corresponding data based on the user's selection

Step 2: Initialize 3D RAMI 4.0 Cube Environment

Set up the 3D plot environment for visualizing RAMI 4.0 cubes
for all stakeholders in M **do**
  Create a 3D RAMI 4.0 cube for each stakeholder using $visual\_config.json$
end for

Step 3: Clustering for Scalability

for all clusters C_k in M **do**
  Calculate the density of each cluster using δ
  if density is below threshold τ **then**
    Assign the entire cluster to a single RAMI 4.0 cube
  else
    Break the cluster into smaller sub-clusters to maintain scalability
  end if
end for

Step 4: Draw Microsystem Representations

for all microsystems in M **do**
  if microsystem is legacy **then**
    Render as a closed system in the Integration Layer
  else
    Visualize the microsystem as an ellipsoid using the following steps:

Ellipsoid Drawing:

    Define vertices of the semi-axes along the RAMI 4.0 dimensions:
      X Coordinates: x_1, x_2 (Hierarchy Levels)
      Y Coordinates: y_1, y_2 (Lifecycle Phases)
      Z Coordinates: z_1, z_2 (Business Layers)
    Compute semi-axis lengths:
      $a = |x_1 - x_2|/2, b = |y_1 - y_2|/2, c = |z_1 - z_2|/2$
    Compute the center of the ellipsoid:
      $h = (x_1 + x_2)/2, k = (y_1 + y_2)/2, l = (z_1 + z_2)/2$
    Define the ellipsoid equation:

$$\left(\frac{(x-h)}{a}\right)^2 + \left(\frac{(y-k)}{b}\right)^2 + \left(\frac{(z-l)}{c}\right)^2 = 1$$

    Draw the ellipsoid in the RAMI 4.0 cube corresponding to its cluster and stakeholder
  end if
end for

Step 5: Visualize Microsystem Interactions

for all interactions in I **do**
  if interaction exists between two microsystems **then**
    Draw a line to represent the interaction, using different line types for intra-cluster, inter-cluster, or inter-stakeholder interactions
  end if

    end for
Step 6: Add Interactive Controls
    Enable user to toggle between different visualizations (e.g., clusters, stakeholders) and apply filters
    Allow for dynamic scaling and interaction within the 3D environment
Step 7: Display the Final 3D Visualization
    Render the final 3D RAMI 4.0 cube visualization with ellipsoids, interactions, clusters, and enhanced functionalities
    Set axis labels to represent RAMI 4.0 dimensions (Hierarchy, Lifecycle, Layers)
    returnFinal 3D plot with all dynamic visual insights
end Function

Algorithm 6: RAMI 4.0 Value Addition Projection.

Inputs:
RAMI 4.0 cubes $\Pi_{stakeholder}$ with microsystems
Value metrics $V = \{v_i\}$ for cost, profit, and environmental impact
System or use case data C
Thresholds for visual scaling
Outputs:
2D projections representing value addition, engineering cost, and microsystem mapping
. . . .
function CREATEVALUEADDITIONPROJECTION ($\Pi_{stakeholder}, V, C$)
Step 1: Initialize
    Load value metrics $V = \{v_i\}$ representing cost, profit, and environmental impact
    Define the 2D projection plane for hierarchy and lifecycle mapping
Step 2: Map Microsystems to RAMI 4.0 Coordinates
    for all $m_i \in \Pi_{stakeholder}$ **do**
        Map microsystem m_i to 2D coordinates (x_i, y_i) based on hierarchy and lifecycle ranges
    end for
Step 3: Represent Microsystems as Ellipsoids
    for all $m_i \in \Pi_{stakeholder}$ **do**
        Draw microsystem m_i as an ellipsoid on the 2D plane
        Assign color to m_i based on its attributes
    end for
Step 4: Apply Value Metrics
    for all $m_i \in \Pi_{stakeholder}$ **do**
        Map profit to value added and cost to engineering cost for each microsystem
        Visualize cumulative value and cost using stair-step representations
    end for
Step 5: Generate Projections for Stakeholders
    for all stakeholders **do**
        Highlight key metrics (e.g., maximum profit, maximum cost)
        Annotate significant points for each stakeholder's contribution
    end for
Step 6: Final Enhancements
    Add a legend for size, color, and line properties
    Enable filters for dynamic exploration of different metrics
    returnFinal 2D projections with value addition, cost, and microsystem mappings
end Function

RAMI 4.0 cube, allowing for an intuitive assessment of the value chain. The algorithm also incorporates interactive features, supporting detailed stakeholder-specific visualizations and enabling dynamic filtering of value flows.

Algorithm 7: Engineering Process Phases and Product Lifecycle Integration Map: Algorithm 7 describes the process of constructing an engineering process phases and product lifecycle integration map. This map visualizes stakeholder involvement across various engineering phases and lifecycle stages, incorporating system components and value metrics. The algorithm highlights the interactions and contributions of stakeholders.

Algorithm 7: Engineering Process Phases and Product Lifecycle Integration Map.

Inputs:
Use case mapped data M from previous steps
Value metrics $V = \{v_i\}$ representing cost, profit, and environmental impact
System components and stakeholder involvement S from system data
Outputs:
2D matrix T showing stakeholder involvement across phases and lifecycle stages

function CREATEINTEGRATIONMAP (M, V, S)
Step 1: Initialize Integration Map
  Set up matrix T with columns representing engineering phases and lifecycle stages, and rows representing stakeholders
  Define engineering phases and lifecycle stages based on RAMI 4.0 architecture
Step 2: Map Stakeholders and Components
  for all $m_i \in M$ **do**
    Retrieve relevant stakeholder and phase information for m_i
    Mark stakeholder involvement in T for each phase and lifecycle stage
    Apply color coding for different stakeholders
  end for
Step 3: Map Component and Stakeholder Interactions
  for all $\sigma_i \in S$ **do**
    Identify stakeholders involved with each system component
    Mark their involvement in T for engineering phases and lifecycle stages
    Apply additional color coding for clarity
  end for
Step 4: Add Value Metrics and Annotations
  for all $v_i \in V$ **do**
    Map cost, profit, and environmental impact for each component in T
    Add annotations or tooltips to cells in T to display these value metrics
  end for
  Add visual connectors or arrows to show interactions between phases and stakeholders
  Enable filtering to toggle between stakeholders, components, and lifecycle stages for detailed views
  returnIntegration map T
end Function

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