Rolling the Dice – Rethinking the RAMI 4.0 Perspectives

Kristof Meixner*† David Hoffmann‡ Sarah Riedmann§ Paula Hünecke‡ Christoph Binder§
*Christian Doppler Laboratory SQI, †Inst. of Information Systems Engineering, TU Wien
E-Mail: [first].[last]@tuwien.ac.at
‡Institute of Ergonomics, Manufacturing Systems and Automation, Otto-von-Guericke U., Germany
E-Mail: [first].[last]@ovgu.de
§Josef Ressel Center for Dependable System-of-Systems Engineering, Austria
E-Mail: [first].[last]@fh-salzburg.ac.at

***Abstract*—As developing current or future industrial systems becomes increasingly complex, new methods for understandably structuring those systems need to arise. The Reference Architectural Model Industrie 4.0 (RAMI 4.0) provides a framework for describing intermingled industrial applications in the context of Cyber-Physical Production Systems (CPPSs). However, although RAMI 4.0 has been standardized for almost a decade, it still lacks actual industrial applications. Recent use cases have shown that the three-dimensional layout might be oversimplified for describing system architectures. Specifically, problems with the so-called live-cycle axis, which has shown significant shortcomings in capturing the dynamics of industrial processes, need to be tackled. This paper provides an analysis of RAMI 4.0 and an assessment of shortcomings that hinder its applicability. It presents alternative approaches that address these limitations by proposing modifications or replacements of parts of RAMI 4.0. Based on the paper's insights, we provide the research agenda for engineering future manufacturing systems, considering it a base for follow-up projects to ensure industrial readiness.**

***Index Terms*—Industry 4.0, RAMI 4.0, Product-Process-Resource.**

I. INTRODUCTION

The Industry 4.0 principles and architectures foundational to industrial systems are increasingly examined for efficacy and relevance. The Reference Architectural Model Industrie 4.0 (RAMI 4.0), established nearly ten years ago, exemplifies an essential framework for guiding the design, development, and integration of Industry 4.0 solutions. It offers a condensed systematic structure essential for implementing smart manufacturing concepts. However, as technology advances rapidly and our understanding of industrial processes deepens, it becomes imperative to reassess the state-of-the-art in industrial architecture. With RAMI 4.0, critical questions arise regarding its relevance, adaptability, and efficacy in addressing industrial control systems' increasingly complex challenges. For instance, the *Life Cycle & Value Stream* axis in RAMI 4.0 is quite reduced in the standard. Furthermore, while the *Hierarchy* axis is more detailed, it misses to place the *Process*, which is the glue between the product and the resources in discrete and continuous manufacturing. This paper aims to explore these questions by providing an overview of reference architectures in manufacturing and proposing novel adaptions of the RAMI 4.0 architecture. Through comparative analysis with RAMI 4.0, we evaluate the strengths and weaknesses of varying architectures, considering factors such as scope, flexibility, interoperability, and applicability to real-world industrial scenarios. To this end, our objective is to shed light on the evolving landscape of industrial architecture and provide insight into the future direction of industrial control system design and development.

In essence, this paper serves as a call to action for the community to critically examine the state-of-the-art industrial system architecture and embrace innovative approaches that pave the way for the next generation of smart manufacturing.

The remainder of this paper is structured as follows. Section II summarizes related work on RAMI 4.0, with shortcomings, and RAMI 4.0 alternatives. Section III presents a morphological box for the reference architecture axes and three alternative representations with a research agenda. Section IV summarizes the paper.

II. RELATED WORK

This section provides related work on RAMI 4.0, shortcomings, and several alternatives.

A. Reference Architecture Industry 4.0

The three-dimensional model has been developed by the Platform Industrie 4.0 to generate a common understanding, including standards, use cases, norms, and other relevant aspects of the industrial sector. The model's scope extends over the entire value-added process and aims to collect and keep consistent technical, administrative, and commercial data [1]. With the networking within the company's means of production and the active cooperation of several factories, RAMI 4.0 fosters the discussion of connections and details. To this end, RAMI 4.0 enables a detailed view of manageable parts of the system but also tasks and processes across the entire process.

The model's core is its vertically arranged layers. Product development and production scenarios are reflected on six levels, such as business, functions, interconnection, and physical aspects. An important characteristic is the high cohesion within and loose coupling between the layers. This means that individual logical units can only perform their intended tasks and be dynamically replaced by other teams.

In addition to the vertical dimension, two additional dimensions are integrated. On the one hand, RAMI 4.0 considers the modeled systems' life cycle, and, on the other hand, it addresses the functional classification within the value chain, creating a horizontal rectangle with each physical unit having a specific place. The second axis of RAMI 4.0 determines the current state during the life cycle of a device. The basis for this is the draft for IEC 62890 [2], which states that a distinction between type and instance is essential.

The third axis is used to classify the components within the factory. Derived from the IEC 62264 [3] and IEC 61512 [4] standards, it specifies a classification scheme from the connected world over the enterprise to the work units. In addition, individual systems, devices, and products are covered, allowing a Cyber-Physical System (CPS) to be classified within the model according to functionality and status.

B. RAMI shortcomings

The comparison of RAMI 4.0 to other reference architectures has shown that it is very generic. While RAMI 4.0 offers a suitable overview of the key concepts within a smart factory, being generic leads to limitations regarding understanding the exact positioning of various technologies and functions and their connectivity. In more detail, planners of smart factories might not know where to locate and place the key concepts within the model's layout, apart from even interconnecting them. This limitation hinders the interplay of various digital twins or digital agents, which is considered the main challenge for planners of smart factories [5].

Another publication emphasizes three potential shortcomings that hinder RAMI 4.0's application [6]:

- The first is the inconsistency within the model's layout. As a product and a production system represent a system, they negatively influence each other when described in a single model. This is substantiated by the definition of a system-of-systems (SoS) and all its disadvantages, like emergent behaviour [7].
- Second, the life cycle is relatively fixed when developing a production system, as they are mainly used during the product's production phase. However, the current alignment of the RAMI 4.0 layers implies that those viewpoints are correlated and should be mutually developed, which impedes the specification of the entire system. Thus, creating a digital twin of the production system would be a better solution to inherit the life cycle axis.
- The third is the missing interoperability of RAMI 4.0. Before its standardization, other approaches to describe production systems were promising that most users still use. Thus, RAMI 4.0 must be supported with suitable interfaces, frameworks, and methods to integrate existing knowledge or expertise and enhance its applicability.

C. Alternatives

This section explores alternative approaches to the three axes proposed by RAMI 4.0: Layers, Life Cycle, and Dimensional Layers. These alternatives draw upon various industrial standards and recommendations, offering insights into alternative frameworks for structuring Industrie 4.0 concepts.

1) Hierarchy Level Alternatives: The Layers axis in RAMI 4.0 delineates different levels of the system hierarchy, facilitating the integration of various components and systems. Alternatives to this axis can provide alternative perspectives on hierarchical structuring within industrial contexts. Examples of alternative approaches include:

ISA88: Integrating the ISA 88 [8] standard within industrial automation systems provides a structured framework for designing and implementing batch control systems. ISA 88, the Batch Control Standard, defines models and terminology for batch manufacturing processes, facilitating interoperability and standardization across industries. Developed by the International Society of Automation (ISA), this standard consists of models such as the Physical Model, Procedural Model, and Recipe Model, collectively addressing equipment, procedural, and recipe aspects of batch processes. Implementing ISA 88 involves applying its models and terminology to design batch control systems, enabling seamless integration and communication between equipment and systems from different vendors. By adopting ISA 88 guidelines, organizations can streamline batch production processes, improve process efficiency, and ensure consistency and quality in batch operations. Compared to RAMI 4.0, the focus of the ISA-88 is more limited and specifically focused on batch control systems, thereby neglecting Enterprise and Site layers.

IEC 62264 and ISA 95: IEC 62264, the Enterprise-Control System Integration (ECSI) standard (cf. Fig. 1) offers guidelines for modeling and integrating manufacturing operations with enterprise systems. Developed by the International Electrotechnical Commission (IEC), this standard defines models for hierarchical levels such as Business, Control, and Equipment, enabling interoperability and data exchange across different layers of the enterprise. Implementing IEC 62264 involves applying its models and methodologies to design integrated control systems, ensuring seamless communication and information exchange between business processes, manufacturing operations, and control systems. By adopting IEC 62264 guidelines, organizations can improve operational efficiency, enhance decision-making capabilities, and achieve greater agility and responsiveness in industrial environments.

The IEC 62264 standard leverages the ISA-95 [9] in conjunction with ISA-88 [8] to establish models for enterprise-control system integration, specifying levels such as Business, Control, and Equipment to enable interoperability and data exchange across different layers of the enterprise. Integrating the IEC 62264 standard within industrial control systems provides a structured framework for enterprise-control system integration. Even though RAMI 4.0 references this standard for its axis, its definition differs.

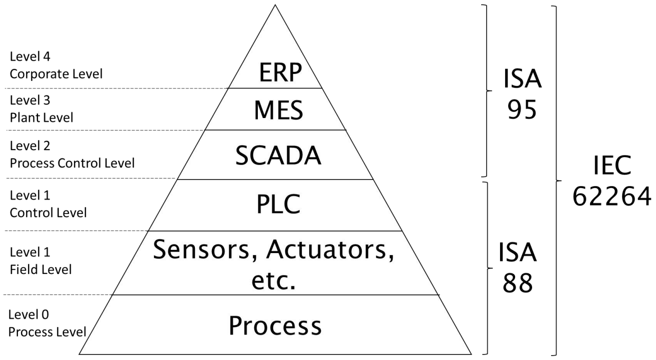

Fig. 1. IEC 62264 automation pyramid [3], based on ISA-88 [8] and ISA-95 [9]

IEC 62443: The integration of the PERA (Process for Enterprise Resilience Architecture) model with the ISA 99 standard established the IEC 62243 standard [10], (cf. Fig. 2) which enhances the security and resilience of industrial control systems. This integration facilitates risk assessment, security controls, and continuous monitoring. Organizations can adopt a comprehensive security strategy to ensure compliance with industry standards and regulatory requirements. Proactively identifying and mitigating cybersecurity risks minimizes the likelihood and impact of cyber incidents on operations, enhancing operational safety and productivity [11]. The model offers a structured framework for designing resilient enterprise architectures across five hierarchical levels, focusing on industrial automation and control systems (IACS) environments. Compared with RAMI 4.0, the upper levels are IT views on the system rather than abstraction towards a business view.

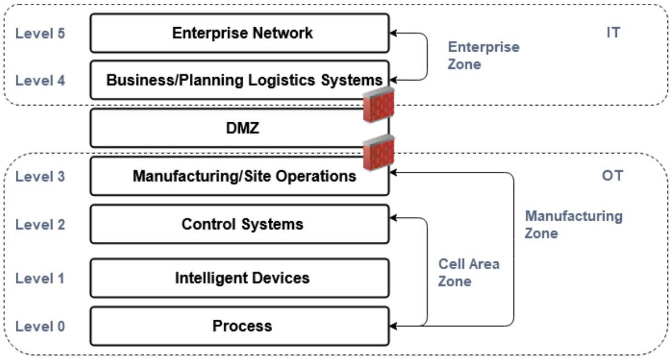

Fig. 2. IEC 62443 hierarchy supporting cybersecurity for CPPS [10], [11]

2) Activity Lifecycle Alternatives: The Life Cycle axis in RAMI 4.0 addresses the entire life cycle of industrial products and systems, from conceptualization to disposal. Alternative frameworks for life cycle management offer different perspectives on managing the life cycle phases of industrial assets. Notable alternatives include:

VDI 2206: The VDI 2206 [12] (cf. Fig. 3) provides a structured approach to developing and implementing manufacturing processes. It offers a systematic methodology for planning, designing, and optimizing production processes, focusing on improving operation efficiency, quality, and flexibility.

VDI 2206 and RAMI 4.0's life cycle axis address the development and operation aspects of industrial systems. However, VDI 2206 focuses on manufacturing processes, encompassing phases such as process planning, design, optimization, and control. It emphasizes the importance of standardization, documentation, and continuous improvement in manufacturing operations to enhance productivity and competitiveness.

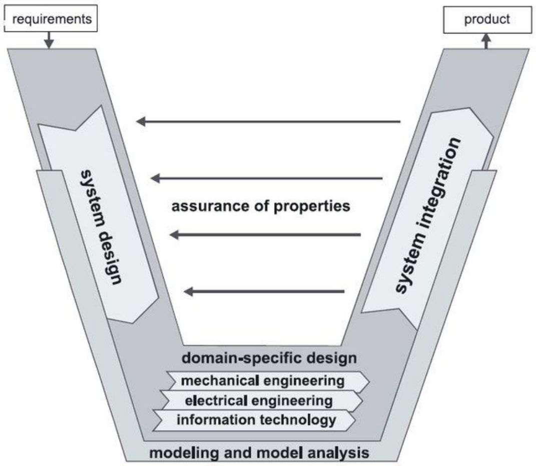

Fig. 3. V-model for CPPS engineering [12]

W-Model: The VDI 2206 guides the development of mechatronic systems, emphasizing systematic analysis of requirements and distribution among disciplines. However, it can lead to integration issues due to independent development. In contrast, the W-model [13] (cf. Fig. 4) addresses these challenges by integrating digital models of discipline-specific solutions for virtual validation. This approach utilizes *Systems Engineering* principles and a formal system model, ensuring compatibility throughout development. While RAMI 4.0 offers a comprehensive framework for industrial system development and operation, the W-model targets specific challenges in the development of active systems, emphasizing interdisciplinary collaboration and virtual validation to ensure seamless integration and compatibility throughout the development process.

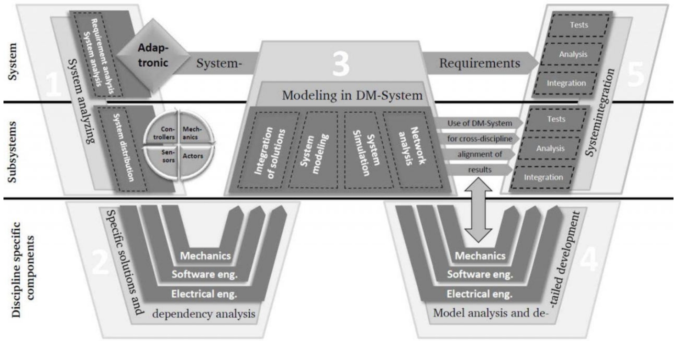

Fig. 4. W-model for CPPS engineering [13]

VDI 3695: VDI 3695 [14] (cf. Fig. 5) outlines a structured approach to product lifecycle management (PLM) in the manufacturing industry. It provides a framework for managing all phases of a product's life cycle, from initial conception to end-of-life disposal, focusing on optimizing processes, resources, and information flow throughout the product's lifecycle.

Comparing VDI 3695 with RAMI 4.0's life cycle axis, both frameworks address the entire life cycle of industrial products and systems. However, VDI 3695 focuses explicitly on product lifecycle management, encompassing product planning, design, development, production, distribution, use, maintenance, and disposal. The guideline emphasizes the importance of integrating PLM processes and tools to ensure efficient and effective management of product data, documentation, and processes across the entire product lifecycle.

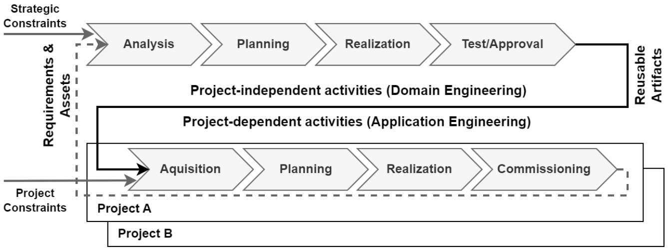

Fig. 5. VDI 3695 model for CPPS engineering [14]

3) Layer alternatives: The Dimensional Layers axis in RAMI 4.0 introduces the concept of multidimensional modeling, enabling the representation of different perspectives on industrial systems. Alternative approaches to dimensional modeling offer diverse ways of conceptualizing and analyzing industrial systems. Examples include:

The IDS-RAM (Industrial Data Space Reference Architecture) [15] provides a framework for structuring and organizing data exchange and processing in industrial settings. It focuses on creating secure, interoperable, and standardized data ecosystems that enable seamless communication and collaboration among industrial stakeholders. IDS-RAM emphasizes the importance of data sovereignty, security, and trustworthiness, allowing organizations to maintain control over their data while facilitating data sharing and integration across different layers of the industrial ecosystem.

Comparing IDS-RAM with RAMI 4.0's layer axis, IDS-RAM offers a complementary perspective on organizing and managing data within industrial environments. While RAMI 4.0's layer axis defines hierarchical layers such as Business, Integration, Communication, and Asset Layers, IDS-RA focuses on organizing data exchange and processing capabilities across different layers of the industrial data space. IDS-RA emphasizes the importance of data interoperability and standardization, enabling seamless integration and data exchange across organizational boundaries.

The IIRA (Industrial Internet Reference Architecture) [16] provides a comprehensive framework for designing and implementing industrial Internet systems. It aims to facilitate interoperability, scalability, and security in industrial settings by defining a standardized architecture that supports various industrial applications and use cases. The IIRA consists of multiple layers, including the Business, Functional, Information, and Communication Layers, each serving specific purposes in enabling data exchange, processing, and decision-making within industrial systems.

Comparing the IIRA with RAMI 4.0's layer axis, both frameworks address the organization and integration of industrial systems but from different perspectives. While RAMI 4.0's layer axis focuses on hierarchical layers such as Business, Integration, Communication, and Asset Layers, the IIRA emphasizes the functional aspects of industrial internet systems, including data processing, analytics, and decision support. The IIRA's layered architecture enables the seamless integration of industrial devices, systems, and applications, facilitating interoperability and scalability in industrial internet environments.

The RFLP (Requirements, Functional, Logical, Physical) approach [17], as part of the Arcadia [18] and SPES methodologies [19], provides a structured framework for system development, particularly in complex and critical systems engineering contexts [17]. It begins with capturing system needs and constraints, then defines system functions to meet those requirements, designs the system architecture at an abstract level, and concludes with implementing the system in hardware and software components. Compared with RAMI 4.0's layer axis, which organizes systems hierarchically, the RFLP approach offers a structured process for defining and implementing system requirements, functions, architecture, and components, facilitating comprehensive system design and development in industrial contexts.

D. Use Case

We utilized the *Fischertechnik testbed* use case, abstracted from a *real-world robot cell for screwing car parts* in the automotive industry [20], [21]. The Fischertechnik testbed comprises (i) a mechanical production system with three conveyors, a turntable, a screwing unit, and a quality control unit with a chute, (ii) an electrical system with sensors and actuators to monitor the system state, and (iii) automation using a WAGO Programmable Logic Controller (PLC) and the corresponding automation program. We plan to test the alternatives compared to RAMI 4.0 on the Fischertechnik testbed.

III. RAMI 4.0 MODIFICATIONS

Based on the existing alternatives for the reference architecture axes, we derived a morphological box [22], from which we can generate new alternatives. Leveraging this box as a starting point, three alternative reference architectures of the RAMI 4.0 were defined that the section subsequently presents.

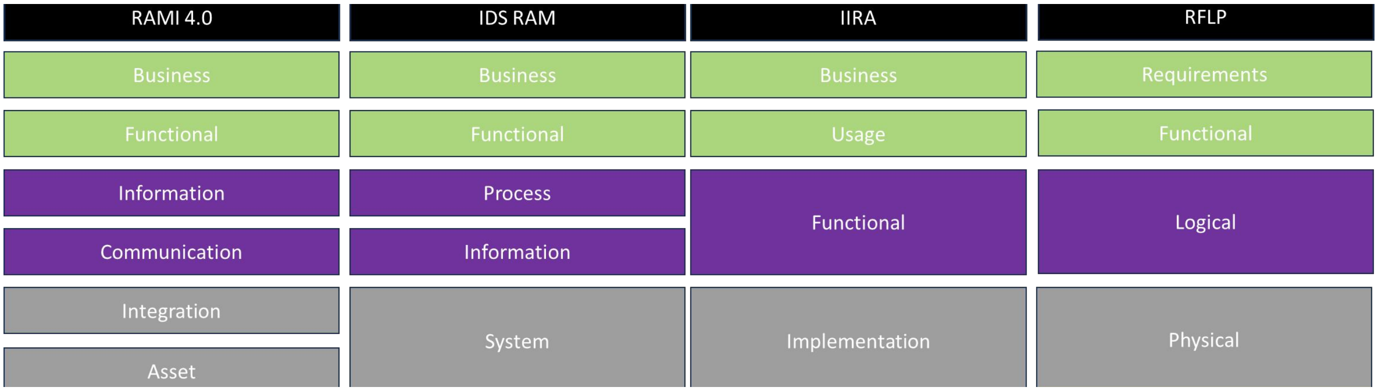

Fig. 6. Layers of RAMI4.0, IDS-RAM, IIRA and RFLP

A. *Morphological Box for Reference Architecture axis*

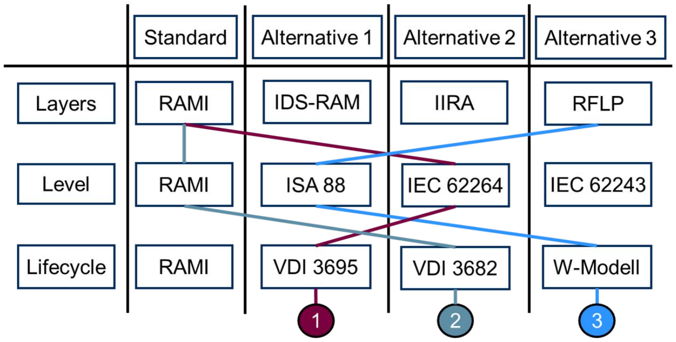

Fig. 7. Morphological Box for Reference Architectures

B. *Presentation of 3 alternatives*

1) Including Asset Reuse: **Motivation:** The *Life Cycle & Value Stream* axis in RAMI 4.0 addresses the asset's type during development and its instance during production, both maintained over their life cycle. While RAMI 4.0 aims to enhance the overall value and considers the entire lifespan of products and systems, it overlooks *reuse and customization*, e.g., reusing and tailoring assets to market or customer demands.

In Software Product Line (SPL) engineering, systematically reusing configurable software components is crucial, providing well-established methodologies and techniques. For instance, it introduced the iterative two-cycle domain and application engineering approach to develop, reuse, and customize software and established models to capture system variability [23]. The VDI 3695 (cf. Fig. 5) used the approach as a reference procedure in Production System Engineering (PSE) [14]. Jazdi et al. [24] investigated which project-independent activities could be conducted more efficiently by identifying and reusing engineering artifacts.

Possible Solution: We propose to extend the *Life Cycle & Value Stream* axis for reuse (cf. Fig. 8). Table I shows the engineering and operation phases in a combined matrix with the RAMI 4.0 layers. Domain and application engineering further define four crucial activities in each phase, i.e., analysis, planning, development and realization, and testing. These activities allow qualified reusable artifacts for a specific target domain, such as automotive manufacturing, to be created and systematically used in CPPS engineering and operation. By integrating such SPL methodologies into RAMI 4.0, we can create a more dynamic framework. This would allow, e.g., for the development of configurable process models that can be easily adapted or reused across different production scenarios, such as a laser welding model modeled in VDI 3682 [25].

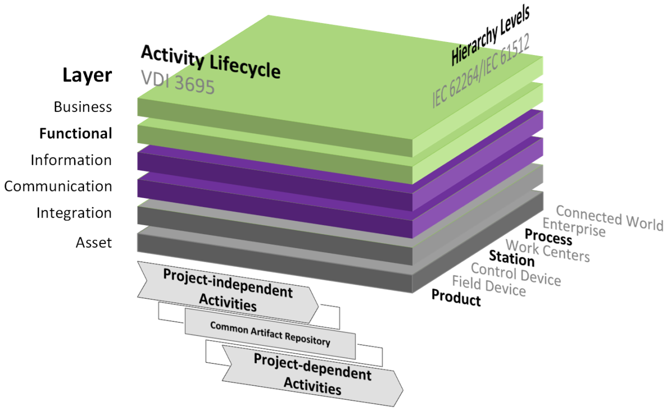

Fig. 8. RAMI 4.0 integrated with VDI 3695 [14]

TABLE I
RAMI 4.0 LAYERS AND VDI 3695 LIFE CYCLE AXIS

	BUS	FUN	INF	COM	INT	ASS
Domain engineering						
Application engineering						
Operation						

Research Agenda: The VDI 3695 and SPL approach are well-established frameworks, yet it is not regularly applied or adopted in the industry. Academic initiatives like CDL-

SQI[1], the CDL-VaSiCS[2], or the SFB1608[3] explore this topic and its industrial applications, but challenges remain. The multidisciplinary nature and modeling dependencies between layers are complex [26], which also holds for reducing the configuration space, especially for production process sequences [27]. Additionally, SPL techniques must be adapted to consider manufacturing economics, such as hardware costs, shop floor space, and return on investment for product types and instances. For the Fischertechnik testbed, we plan to derive reuse and variability models for domain engineering.

2) Combination with PPR - separation of concerns: **Motivation:** As shown in several scenarios [5], [6], using all three dimensions results in high complexity, which hinders the applicability of RAMI 4.0. As this three-dimensional reference architecture addresses the aspects of a production system, including all available resources and the product during its life cycle and across multiple viewpoints, several inconsistencies emerge. For example, within most industrial systems, it is not necessary to take the life cycle of a production resource into account, as it is solely used during the Instance/Production phase in most cases. When building a machine from scratch, it might be considered a resource again. On the other hand, the product is seen as a single row within the automation pyramid that does not span all three dimensions. Thus, a possible solution might be to separate the concerns of the production system and the product within RAMI 4.0 by splitting the entire cube.

A well-established standard supporting this is the VDI 3682 [25] for formalized process descriptions distinguishing a production process into product, process, and resource. While a product represents the physical object to be manufactured, it has different production steps and characteristics during its life cycle. The process row of RAMI 4.0 is determined to model the specifications of a product. A process, however, is used to transform the product into required characteristics and describes which tasks must be performed. How such a process could be located within RAMI 4.0 is still unclear. Finally, the resources aim to execute the tasks defined by the process. To do so, a resource hierarchy needs to be available, which could be ideally modeled across the automation pyramid axis of RAMI 4.0.

Possible Solution: In conclusion, reducing the framework to two matrices with two axes would contribute to a better understanding of the interconnections in flexible production systems. This is underpinned by the fact that the *Life Cycle & Value Stream* axis mainly targets the value creation possibilities of smart products instead of whole production systems. The other two dimensions of RAMI 4.0, the automation pyramid and the interoperability layers, describe the production system. Their interplay spans a matrix, as shown in Table II.

TABLE II
INTERCONNECTION MATRIX OF HIERARCHY LEVELS WITH INTEROPERABILITY LAYERS

	BUS	FUN	INF	COM	INT	ASS
Connected World						
Enterprise						
Work Unit						
Station						
Control Device						
Field Device						

Within this matrix, greenfield systems can be developed from scratch using top-down engineering approaches, or brownfield systems could be modeled by locating them in the different panes, according to automation pyramid level or viewpoint to consider. However, as far as the product is concerned, the corresponding matrix, as indicated in Table III, should be applied. With this table, a product is modeled throughout the entire life cycle, from raw material acquisition to first blueprints, used products, or maintenance after installation. The needed resources to overtake these steps are those shown in Table II.

TABLE III
PRODUCT MATRIX OF HIERARCHY LEVELS WITH LIFE CYCLE AXIS

	BUS	FUN	INF	COM	INT	ASS
Type/Development						
Type/Maintenance						
Instance/Production						
Instance/Maintenance						

This means that the production system and product architectures must somehow be interconnected. According to Industry 4.0 and the concept of flexible production systems, each single product could have a different allocation of resources, realized by the production process. Thus, each product might have an individual process performed on individual resources for each instance. An advantage of this method is that a single resource within the production system might be considered a product in another domain. The life cycle of this product can be separately described and represented with the process. In the original system, this resource is only used during its utilization. Therefore, multiple instances of RAMI 4.0 could describe the same system across various scenarios and manufacturers.

To summarize, by slitting RAMI 4.0 and dividing it into these three concepts, a product, a production process, and a resource could be developed and defined independently. At the same time, an interconnection ensures the traceability within the production network. This would contribute to the applicability of RAMI 4.0 and reduce its complexity by reducing the engineering space by one dimension.

Research Agenda: While the matrix addressed by Table II has already been used in several projects and has proven to be a promising concept, its interconnection with the product and the production process needs to be further investigated. Thus,

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[1] CDL-SQI: https://sqi.at

[2] CDL-VaSiCS: https://www.jku.at/cdl-vasics/

[3] SFB1608: https://www.sfb1608.kit.edu

future studies should focus on aligning the separate matrices with the production process to create a flexible production system. Promising concepts to analyze as possible solutions could be the specification of reference architectures targeting particular production areas or simulation environments. For the Fischertechnik testbed, we plan to test a reconfiguration simulation for products.

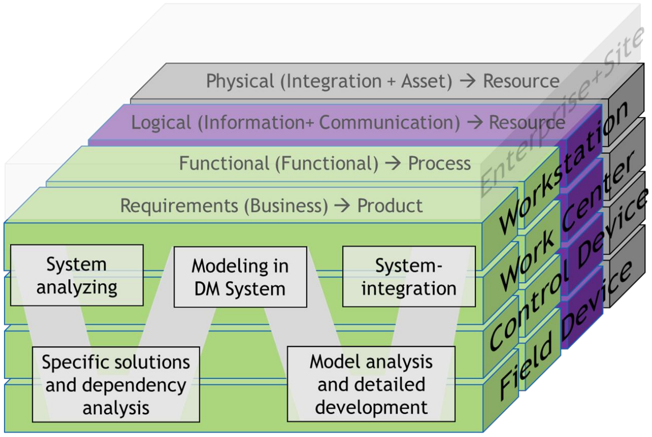

Fig. 9. The RAMICS model

3) Reference Architecture Model for Industrial Control System - RAMICS: **Motivation:** The motivation behind proposing RAMICS (Reference Architecture Model for Industrial Control Systems) lies in the need for a specialized framework tailored specifically for the automation and improvement of existing production system concepts. While the RAMI 4.0 (Reference Architecture Model for Industry 4.0) provides a solid foundation for Industry 4.0 implementations, it lacks the granularity required to address the unique challenges posed by industrial control systems. By remixing the RAMI 4.0 architecture and incorporating principles from MBSE (Model-Based Systems Engineering) and ISA88 (International Society of Automation Standard for Batch Control), RAMICS aims to provide a more focused and comprehensive framework for designing, implementing, and managing industrial control systems.

Advantages Compared to RAMI 4.0: RAMICS offers several advantages over RAMI 4.0. Firstly, by adopting the RFLP (Requirements, Functional, Logical, Physical) layers from MBSE, RAMICS provides a structured approach that ensures clarity and consistency throughout the development lifecycle. Secondly, utilizing the W-model for lifecycle management enhances the reliability and performance of control systems by emphasizing early validation and verification. Thirdly, by focusing specifically on control architecture by incorporating ISA88 layers, RAMICS provides a targeted approach that addresses the industrial automation and control requirements. RAMICS offers a more streamlined and efficient framework for designing and managing industrial control systems compared to the broader scope of RAMI 4.0.

Disadvantages compared to RAMI 4.0 While RAMICS offers several advantages over RAMI 4.0 in the context of industrial control systems, it's essential to consider potential disadvantages as well: *Limited Scope*: One disadvantage of RAMICS compared to RAMI 4.0 is its narrower focus on industrial control systems. While this focus allows for a more detailed and specialized approach, it may limit the applicability of RAMICS to broader Industry 4.0 initiatives encompassing a wide range of technologies and processes beyond control systems. *Interoperability*: RAMI 4.0, with its comprehensive layers and cross-cutting aspects, emphasizes interoperability between various components and systems within the industrial ecosystem. In contrast, the more specialized nature of RAMICS may pose challenges in achieving seamless interoperability with other systems and components outside control architecture. *Complexity Reduction*: RAMI 4.0 provides a hierarchical structure that simplifies the complexity of Industry 4.0 implementations by organizing components into layers and aspects. RAMICS, while tailored for control systems, may lack the same level of hierarchical organization, potentially leading to increased complexity in system design, integration, and management. *Adaptability to Future Technologies*: RAMI 4.0 is designed to accommodate emerging technologies and evolving industry standards, providing a flexible framework for future-proofing industrial systems. RAMICS, with its narrower focus on control architecture and specific methodologies, may be less adaptable to rapid technological advancements and changes in industry practices. *Standardization and Adoption*: RAMI 4.0 has gained widespread recognition and adoption as a reference architecture for Industry 4.0 initiatives. In contrast, RAMICS, being a specialized framework, may face challenges in achieving similar standardization and widespread adoption, notably if it diverges significantly from established industry norms and practices.

In summary, while RAMICS offers tailored advantages for industrial control systems, it may also face limitations compared to the more comprehensive and widely adopted RAMI 4.0 architecture regarding scope, interoperability, complexity reduction, adaptability, and standardization.

Applicable Use Cases: RAMICS is well-suited for various use cases in industrial automation and control. Though more limited than standard RAMI 4.0, its incorporation of batch control principalities makes it well-suited for industrial settings. Therefore, engineers can apply it in manufacturing environments to automate production processes, optimize resource utilization, and improve overall efficiency. In process industries such as chemical, pharmaceutical, and food and beverage, RAMICS can facilitate batch control, recipe management, and quality assurance.

Research Agenda: Further research is needed to validate and refine the RAMICS framework and its associated methodologies. An overall consideration shall be laid on enabling the interoperability with RAMI 4.0, e.g., by further specifying the layers' contents. Empirical studies are needed to assess the effectiveness of RAMICS in real-world industrial settings, case studies are needed to demonstrate its applicability across different industries, and comparative analyses are needed to evaluate its advantages over existing approaches. Additionally, research efforts should focus on extending and customizing RAMICS to address specific industry requirements and emerging technologies such as IoT (Internet of Things), AI (Artificial Intelligence), and Cybersecurity. By advancing the research agenda for RAMICS, we can contribute to the ongoing evolution of industrial control systems and drive innovation in industrial automation. As a first step, we will model the Fischertechnik testbed's WAGO system with RAMICS.

IV. CONCLUSION

The RAMI 4.0 provides the foundation for structuring the engineering and the operation of complex CPPSs. However, its application has been limited by several challenges, including its simplified layout and the rigidity in accommodating the linear lifecycle of industrial assets. These shortcomings highlight the need for a more dynamic and flexible architecture.

This paper has presented three alternatives to the traditional Reference Architectural Model Industrie 4.0 (RAMI 4.0) structure, each aiming to address specific limitations. Firstly, integrating SPL engineering principles enhances the reuse and customization of assets, fostering more agile and responsive manufacturing systems. Secondly, proposing a reduced, more focused framework by separating concerns between product and production systems offers clarity and reduces complexity. Lastly, the introduction of RAMICS tailors the reference architecture specifically for industrial control systems, aligning more closely with the operational demands.

The research agenda focuses on empirically validating these alternatives through pilot implementations and industry collaborations. To this end, future work will seek to refine their applicability, ensuring that they investigate and address the current gaps in RAMI 4.0. The aim is to establish a more robust, scalable, and interoperable architectural standard that aligns with the future vision of Industrie 4.0 touches production as a service.

ACKNOWLEDGMENT

The financial support by the Christian Doppler Research Association, the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Research, Technology and Development is gratefully acknowledged. This work has been supported and funded by the Austrian Research Promotion Agency (FFG) via the Austrian Competence Center for Digital Production (CDP), contract 881843

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