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A Review of Reference Architectures for Industry 4.0 and Their Impacts in Smart Manufacturing

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Abstract

Industry 4.0 can potentially become the global production language by integrating existing and new technologies to address contemporary manufacturing challenges. Establishing uniform industry standards is central to its successful implementation, necessitating a global effort towards standardization with international cooperation and a systemic perspective. Uniform technical standards are essential for a network connecting diverse factories and companies. Significant progress has been made in standardization efforts, focusing on technologies like the Internet of Things (IoT) and Cyber-Physical Systems (CPS), pivotal to Industry 4.0. One key initiative is the Reference Architecture Model for Industry 4.0 (RAMI 4.0), which employs a three-dimensional coordinate system describing all essential components of Industry 4.0. This system enables the decomposition of complex interrelations into manageable subsystems, clusters, or modules. Another crucial standardization effort is the Industrial Internet Reference Architecture (IIRA), developed by the Industrial Internet Consortium (IIC). IIRA is an open, standards-based architecture designed to manage interoperability, map applicable technologies, and guide technology and standards development. The IIRA framework supports various system types, configurations, and connections across multiple industries and use cases. The rapid growth and evolution of IoT present significant challenges to standardization. However, standardization is crucial for the further development and widespread adoption of IoT technologies, primarily aiming to enhance interoperability among different applications and systems. Efforts ensure that devices and applications from other countries can exchange information seamlessly. Key standards in IoT include communication standards, identification standards, and security standards, which are major drivers for adopting IoT technologies. In this study, comprehensive and uniform standards were reviewed to realize Industry 4.0's strategic vision. Continued international collaboration and a focus on addressing specific standardization challenges were essential to achieve global integration and optimization of manufacturing processes.

Keywords

Industry 4.0, RAMI 4.0, Smart Manufacturing, Reference Architecture, Digitization

1. Introduction

Germany is renowned for having one of the world's most competitive manufacturing industries, particularly in manufacturing equipment. This success is primarily due to Germany's focus on research, development, and production of innovative manufacturing technologies and its expertise in managing complex industrial processes. Germany's strong manufacturing infrastructure, significant information technology competencies, and proficiency in embedded systems and automation engineering position the country as a global leader in manufacturing technology (Xu et al. 2018).

Industry 4.0 represents a new era of industrialization, driven by integrating the Internet of Things (IoT) and services into the manufacturing environment. This fourth industrial revolution follows the earlier mechanization, electricity, and I.T. revolutions. It envisions the creation of global networks that incorporate machinery, warehousing systems, and production facilities such as cyber-physical systems (CPS). CPS consists of intelligent machines, storage systems, and production facilities that autonomously exchange information, initiate actions, and control each other. This enhances industrial processes, including manufacturing, engineering, material usage, supply chain, and lifecycle management (Lee et al. 2015). Smart factories, a key component of Industry 4.0, utilize a new production approach where smart products are uniquely identifiable, traceable, and aware of their history, status, and alternative production routes (Shadravan and Parsaei 2022). Embedded manufacturing systems in Industry 4.0 are vertically integrated with business processes within factories and horizontally connected to dispersed value networks, enabling real-time management from order placement to outbound logistics. This end-to-end engineering integration across the value chain allows for customized production, flexibility in responding to disruptions, and improved decision-making through transparency (Shadravan and Parsaei 2023A).

Figure 1 illustrates the phases of the Industrial Revolution. Assessing an organization's digital maturity is a critical initial step in developing an effective digitalization strategy, as it identifies process strengths and areas for improvement. Digitization enhances access to information, improves communication, increases opportunities for product development, introduces new business sectors, removes regulatory barriers, and enhances knowledge acquisition. This enables SMEs to compete with larger enterprises in terms of price and product quality. However, as SMEs undertake digital transformation, they face additional challenges, including new dependencies and significant risks concerning data protection and information security (Shadravan and Parsaei 2023B).

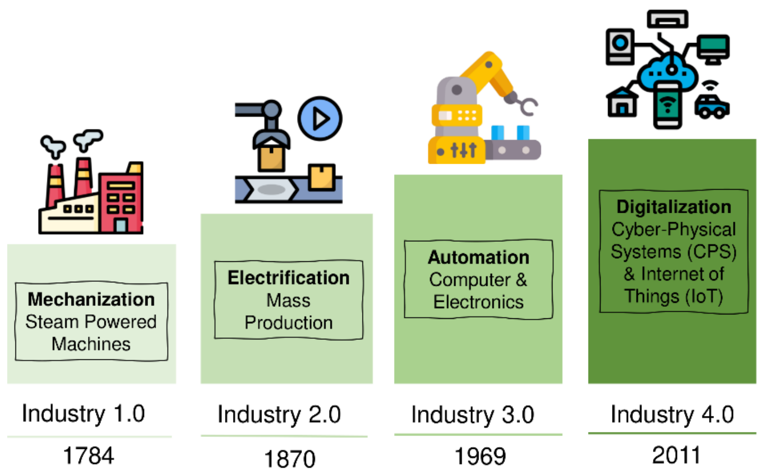

Figure 1. Industrial Revolution Stages: Industry 1.0 through Industry 4.0 (Shadravan and Parsaei 2023C)

2. Literature Review

Industry 4.0 holds significant potential for enhancing resource and energy efficiency, promoting urban production, and addressing demographic changes. Smart factories enable the profitable production of individualized items and allow dynamic business and engineering processes to adapt to last-minute changes and disruptions. This new industrial paradigm also offers startups and small businesses opportunities to develop downstream services, fostering innovation and new business models. However, global competition in the manufacturing sector is intensifying, and Germany is not alone in recognizing the importance of IoT; competitors in Asia, other European countries, and the U.S. are also advancing in this field. Germany must adopt a dual strategy to maintain its leadership: integrating information and communication technology into its traditional high-tech strategies and creating new markets for CPS technologies and products (Shadravan and Parsaei 2023D).

To fully realize the potential of Industry 4.0, several key areas must be addressed. Establishing common standards and a reference architecture is essential for facilitating collaboration across value networks. Engineers need to be equipped with tools and methods to manage the increasing complexity of products and manufacturing systems. Expanding reliable, high-quality communication networks within Germany and with partner countries is crucial for broadband infrastructure. Ensuring the safety and security of smart manufacturing systems, including data protection against misuse and unauthorized access, is paramount. Implementing socio-technical work organization approaches will enhance worker responsibility and personal development. Developing training strategies to transform job and competence profiles and promoting lifelong learning and workplace-based continuing professional development is vital. Adapting legislation to address the challenges of Industry 4.0, such as data protection, liability, and trade restrictions, will provide a necessary regulatory framework. Enhancing resource productivity and efficiency, balancing the investment in intelligent factories with potential savings, is essential for resource efficiency. The transition to Industry 4.0 will require substantial research and development (R&D) efforts, focusing on manufacturing systems' horizontal and vertical integration and end-to-end engineering integration. New social infrastructures in the workplace and the continuous development of CPS technologies are also critical and should be supported by appropriate industrial policies to ensure successful implementation. The evolution towards Industry 4.0 will enhance Germany's global competitiveness and sustain its domestic manufacturing industry by leveraging innovative solutions, extensive R&D, and a robust policy framework (Shadravan and Parsaei 2024).

The Benefits of Standardization: Standardizing architectures, data exchange formats, semantics, vocabularies, taxonomies, ontologies, and interfaces is crucial for achieving interoperability among the various technologies within Industry 4.0. Experts agree that multiple specialized standards will emerge over the next few years, enabling interoperability across diverse systems. Germany and international standardization efforts should focus on semantic interoperability, standard data formats, and domain models. Experts from Germany and Japan emphasize the importance of reference models, while Chinese experts prioritize a standard Industry 4.0 vocabulary. Key issues in standardization include developing interoperable interfaces between different manufacturers' solutions and establishing open standards. Without these, isolated, proprietary solutions could lead to technological lock-in and high switching costs, especially for small and medium-sized enterprises (SMEs). Open standards increase market potential for SMEs by providing access to a more extensive customer base and complementary products. Standardization organizations must work closely with industry to address technological gaps efficiently. German organizations should engage more with international consortia, like the Industrial Internet Consortium (IIC) and the Object Management Group (OMG), to maintain their prominent role in global standardization. Despite the slow progress due to the complexity of Industry 4.0, experts stress the need for closer international cooperation to accelerate standardization activities.

Standardization is essential for interoperability and portability in combining different systems within Industry 4.0. Key factors influencing the process include stakeholders' interest in establishing standards and their preference for open or closed standards. Open standards facilitate rapid and widespread adoption but are more challenging to monetize, while closed standards promise higher returns for technology suppliers. Suppliers of Industry 4.0 solutions must weigh the benefits of market penetration against maintaining relative market power. Strengthening the international dimension of German Industry 4.0 activities can benefit from global interest in German solutions. Engaging more in international standardization organizations and seeking leadership roles can use international standardization as a catalyst for cooperation. Promoting collaboration between innovation centers will create stronger links to facilitate cross-border cooperation. Developing an integrated Industry 4.0 strategy alongside pragmatic, high-profile solutions will make the benefits of Industry 4.0 tangible.

In the U.S., Industry 4.0 encompasses technological advancements and new business models like innovative services and big data analytics. Silicon Valley firms see the transition to a network economy as an opportunity for exporting sensor and wireless technologies. The U.S. perceives the opportunities of Industry 4.0 as more significant than the risks, driven by private sector consortia like the IIC, which aim to ensure interoperability through reference architectures, frameworks, and open standards. The U.S. approach is collaborative, with companies from outside the U.S. constituting a significant portion of consortium members. The risk for Germany is that U.S. consortia could establish "quasi-standards" quickly, potentially sidelining German companies. To strengthen trade relations in Industry 4.0, Germany should leverage strong trade ties with the U.S. and capitalize on the reindustrialization of the American economy. Ensuring long-term corporate strategies integrate future business models and maintaining control when collaborating with software firms will help maintain control over Industry 4.0 business models. Establishing industry-specific platforms for SMEs will ensure fair cooperation with large U.S. Internet companies. Actively managing ideas and talent through strategic partnerships with U.S. companies and research institutions will foster innovation and development (Rojko 2017).

The analysis of enabling technologies reveals three distinct levels of intelligence: Control, Integration, and Intelligence. The control level encompasses computer numerical control (CNC), programable logic control (PLC), and statistical analysis, which enhance production efficiency and reduce labor dependency. The Integration level builds upon control technologies by incorporating IoT and cyber-physical systems (CPS), creating interconnected digital manufacturing environments. This integration enables communication between control systems and collecting data from various sources, including sensors, machines, production lines, manufacturing control and management systems, customer feedback, and the supply chain. This collected data provides insights into improving manufacturing processes. At the Intelligence level, the data gathered at the integration stage is utilized for planning and decision-making through advanced technologies like data mining and big data analysis. Manufacturing systems at this level demonstrate self-awareness, self-optimization, and self-configuration, fully embodying Industry 4.0 principles. Applications at the Intelligence level represent the practical realization of Industry 4.0 concepts. The primary objectives of Industry 4.0 include the vertical integration of I.T. systems in production and automation, the horizontal integration of various I.T. systems across the value chain, consistent engineering throughout the entire lifecycle, and the customization of products, even in small lots or single units.

Furthermore, Industry 4.0 seeks to create new social infrastructures for employment. Digital twins are essential for realizing Industry 4.0 principles, necessitating using specific software platforms to automate industrial processes. Over the last two decades, reference designs have become popular among businesses and organizations as blueprints for designing and integrating software-intensive systems. These designs encapsulate the key features of a domain's systems, guiding software development, standardization, and evolution. These architectures, developed by consortiums of key industrial players and researchers, improve interoperability, save development costs and time through reuse, lessen software project risks, improve communication, and promote best practices (Heidel 2019).

Industry 4.0 employs reference architectures with varying content, formats, and purposes to address different scenarios and challenges. Each scenario corresponds to a unique use case with distinct architectural requirements. However, the suitability of current Industry 4.0 reference architectures for specific use cases remains underexplored. Therefore, it is essential to identify and understand these reference architectures, how they can be tailored for specific innovative factory use cases, and the supporting technologies and tools available. Previous studies offered two or three reference designs for Industry 4.0 but did not properly investigate their core structures and elements, making it difficult to assess their genuine capabilities (Bitkom et al. 2016) (Alcácer and Cruz 2019).

By conducting research on the most recent pertinent Industry 4.0 reference architectures, aligning them with the industrial automation pyramid, and going over the tasks, tools, and technologies required to modify a reference design for a particular Industry 4.0 project, businesses can effectively integrate advanced technologies, optimize operational efficiencies, and enhance overall productivity while ensuring seamless interoperability and scalability within their industrial systems. This paper highlights the critical need for solid reference designs to propel the creation and advancement of Industry 4.0 systems and develop of intelligent factories through methodical investigation and analysis.

Reference Architectures of Industry 4.0: The US-led Industrial Internet Consortium (IIC) developed the Industrial Internet Reference Architecture (IIRA), a comprehensive, industry-driven framework, to promote the worldwide implementation of the Industrial Internet of Things (IIoT) across a range of industries, including manufacturing, healthcare, energy, and smart cities. The Reference Architectural Model Industry 4.0 (RAMI 4.0) is a domain-specific, government-endorsed architecture recognized internationally as IEC PAS 63088:2017. It was developed by a consortium led by the Association of German Engineers (VDI) and the German Electrical and Electronic Manufacturers' Association (ZVEI). Japan's Industrial Value Chain Initiative maintains the Industrial Value Chain Reference Architecture (IVRA), a conceptual framework. A multi-layered academic architecture known as the Stuttgart IT-Architecture for Manufacturing (SITAM) was created at the University of Stuttgart in Germany through research programs. The University of Ljubljana in Slovenia has designed a two-dimensional architecture called LAsim Smart Factory (LASFA). Furthermore, IBM provides an Industry 4.0 reference architecture available for purchase (Nakagawa et al. 2021).

These architectures were introduced and revised at various times and are described in full in external sources. In particular, the Industry 4.0-focused initiatives IIRA and RAMI 4.0 were introduced in 2015, almost four years after the notions of smart factories and Industry 4.0 gained traction. The IIRA emphasizes industrial features like business operations, forecasting, efficiency, device monitoring, and information analytics by utilizing experience with IoT systems. RAMI 4.0, on the other hand, attempts to create a shared understanding among interested parties by offering a general perspective on innovative manufacturing structures. The evolution of these architectures, such as the IIRA's progression to version 1.9, showcases continuous enhancements and alignment with Industry 4.0 system development, technological advancements, and a deeper understanding of Industry 4.0's scope. These frameworks, created and improved in close cooperation with businesses or via university research intimately related to business initiatives, as in SITAM and LAFSA cases, represent the sector's innovations and practical demands. RAMI 4.0, IVRA, and IIRA were created and enhanced by consortiums of businesses and academic institutions, assuring their applicability and easing their adoption. These reference architectures are categorized based on perspective, purpose, and context, and adapted to the context of this research as depicted in Figure 2.

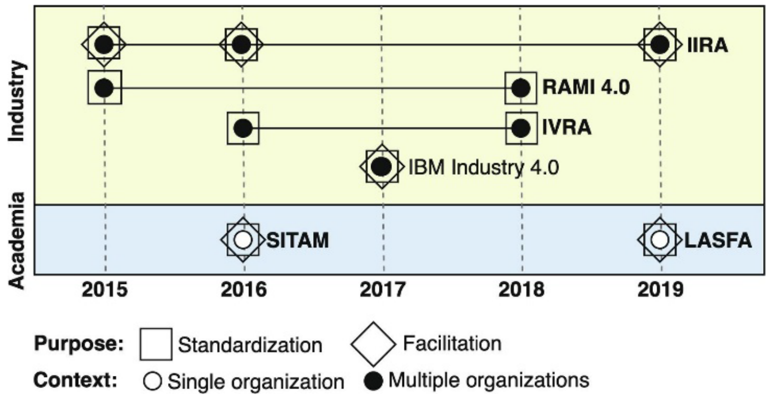

Figure **2.** Release year, goals, and Industry 4.0 application context for reference architectures

(Nakagawa et al. 2021)

Perspective:
An architecture is deemed "classical" if it compiles best practices from various established and utilized software systems within a domain. If such systems are not yet in place, the architecture is labeled as "preliminary." All Industry 4.0 reference architectures fall into the preliminary category, as the extensive adoption and maturation of Industry 4.0 systems in factories will require more time.

Purpose:
The primary goal of all reviewed architectures is standardization. This promotes effective stakeholder communication and understanding and enhances system and component interoperability. Additionally, the IIRA, IBM Industry 4.0, SITAM, and LASFA architectures aim to facilitate knowledge sharing and reuse related to Industry 4.0 system architectures. These four architectures are discussed in detail, emphasizing their components and interrelationships.

Context:
Architectures developed by consortia (IIRA, RAMI 4.0, IVRA) and commercial entities (IBM Industry 4.0) are intended for use by multiple organizations, while academic architectures (LASFA and SITAM) usually target one or a few organizations. This suggests that these architectures require further development and broader industry adoption to reach maturity. Once matured, they could transition to a classical perspective, incorporating practical experience from various systems. This would aid in the advancement of Industry 4.0 structures across multiple organizations and promote the extensive reuse of knowledge and experience.

RAMI 4.0:
The RAMI 4.0 model integrates various aspects of Industry 4.0 for smart manufacturing by combining all elements and I.T. components across different layers, hierarchical levels, and the product lifecycle. It serves as a three-dimensional framework offering guidelines and rules to structure, organize, and classify technical content. RAMI 4.0 was developed to achieve several key goals: identifying existing standards, addressing gaps and loopholes, and resolving overlaps. This comprehensive approach ensures a more structured and cohesive implementation of Industry 4.0 principles. Industry 4.0 reference designs were interpreted using the conventional industrial automation pyramid as a reference. This pyramid includes five levels: control (Programmable Logic Controllers and PID controllers managing single devices), field (physical entities like machines and sensors), system/process (SCADA systems managing multiple devices), operation (Manufacturing Execution Systems (MES) overseeing the entire production process), and enterprise (Enterprise Resource Planning (ERP) systems for integrated company management). However, in Industry 4.0, the boundaries between these levels are increasingly blurred, transforming into a meshed network based on the need for plant complexity and production flexibility.

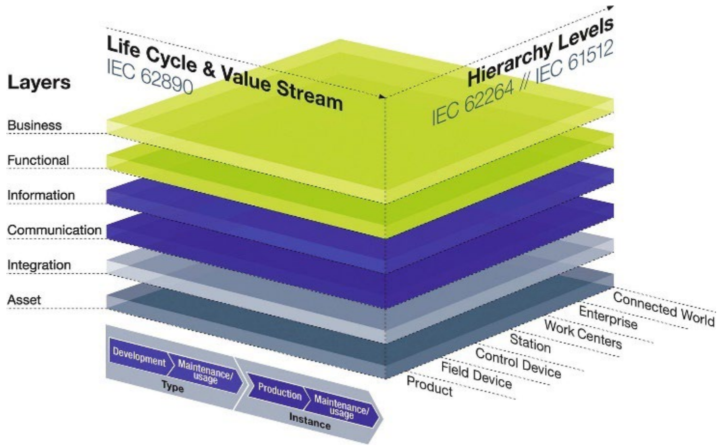

Figure 3. Reference Model RAMI4.0 (Heidel 2019)

Figure 3 shows RAMI 4.0; the vertical axis layers highlight the need to integrate all aspects of enterprise digitalization, comprising: Asset Layer: Encompasses physical elements like robots and conveyor belts, as well as software and other non-physical objects, connecting to the digital realm through the Integration Layer. Integration Layer: Converts asset information into digital form, linking components to I.T. systems via sensors and RFID readers and reflecting key events in the virtual world. Communication Layer: Ensures standardized communication with uniform data formats and predefined protocols, aiding the Integration Layer. Information Layer: Transforms and integrates data into valuable information, aligning events with the next layer's data requirements. Functional Layer: Provides detailed descriptions of functions, offering a platform for horizontal integration, remote access, business procedures, and decision-making logic. Business Layer: Maps and connects various business models, ensuring coherence within the value stream and supporting the migration from current to future manufacturing setups.

3. Methodology

In this paper, four distinct research questions (R.Q.s) were developed to methodically investigate whether the reference designs that are already in use are appropriate for facilitating Industry 4.0 processes. To determine the extent of current architectures concerning intelligent factory systems, RQ1 aims to determine which layers of the pyramid of industrial automation are covered by the Industry 4.0 reference architectures. RQ2 looks at the documenting of architecture in terms of detail since thorough documentation improves its practical applicability. The goal of RQ3 is to ascertain the procedures needed to modify the architectures for Industry 4.0 applications. Based on these architectures, RQ4 investigates the technology and instruments required to create Industry 4.0 systems. When taken as a whole, these inquiries offer a methodical way to evaluate the applicability and usefulness of Industry 4.0 reference designs. RAMI 4.0 is designed as a three-dimensional framework to systematically address Industry 4.0 challenges, ensuring clear communication among all participants involved. As a service-oriented architecture, RAMI 4.0 integrates all elements and I.T. components into a cohesive layer and lifecycle model.

Breaking down complex processes into easily understandable segments effectively tackles data privacy and I.T. security issues. Each architecture has unique contributions. RAMI 4.0 and IVRA provide frameworks for organizing smart factories. RAMI 4.0 uses a three-dimensional structure based on international standards, detailing value streams, hierarchy levels, and layers. IVRA offers a comprehensive view of smart factory components and their integration, represented in layers like Business, Activity, and Specification. IIRA focuses on the functionalities required for industrial domains, drawing from IoT system architecture experiences. It details technical issues and functional components, their structure, interrelations, and interactions with external elements.

SITAM emphasizes integration and interoperability through middleware, which connects various systems throughout the product lifecycle. IBM Industry 4.0 provides commercial tools to automate its components and balance workloads. Digital Twins are crucial for early problem detection and predictive maintenance and are addressed by IIRA, RAMI 4.0, and LASFA. However, while these architectures include digital twins at a high level, they offer limited details on real-world entity connections and specific applications. Recent developments based on IIRA and RAMI 4.0 have further advanced digital twin applications. Intelligence and big industrial data, critical elements of Industry 4.0, are briefly mentioned by IBM Industry 4.0, SITAM, IIRA and LASFA, with recommendations for using machine learning and data mining. However, there is still a lack of comprehensive data on data processing enabling cognitive and decision-making functions in smart factories.

4. Discussion

The current iterations of Industry 4.0 reference architectures lack sufficient detail to make their use in industrial projects straightforward. These architectures do not offer specific guidelines for customization, with only a few examples, such as IIRA, RAMI 4.0, and SITAM, providing some direction for project-specific adaptation. These examples underscore the necessity for clear, concrete steps to tailor the architectures to meet requirements. Commercial architectures like IBM Industry 4.0 are more frequently discussed in gray literature than in scientific publications, highlighting the need for detailed customization guidelines for each architecture to promote wider industry adoption. To address all R.Q.s: RQ1: Industry 4.0 reference architectures like RAMI 4.0 cover all levels of the automation pyramid, including sensors and actuators (field level), PLCs (control level), SCADA systems (supervisory level), MES (planning level), and ERP systems (enterprise level), ensuring comprehensive integration. RQ2: Industry 4.0 reference architectures provide detailed descriptions across multiple layers and levels, such as RAMI 4.0's asset, integration, and business layers. However, they often lack specific guidance on communication processes and data exchanges. RQ3: These architectures can be tailored through customization, modular design, and flexible integration, adapting to industry needs with modular components and real-time connectivity, supported by detailed guidelines and standardized communication protocols. RQ4: Key technologies include sensors, PLCs, SCADA systems, MES, ERP systems, IoT platforms, big data analytics, cloud and edge computing, cybersecurity solutions, and digital twins, along with standardized communication protocols like OPC UA.

5. Conclusion

The lack of sophisticated technologies and standardization makes Industry 4.0 implementation difficult and affects both large firms and SMEs. Despite this, interest in Industry 4.0 is growing, with numerous standardization efforts and research projects emerging. This work reviews key reference architectures, highlighting their value and guiding sustainable development. A major challenge is defining information and communication flows for interoperability in smart manufacturing. Existing architectures outline layers and communication but lack detailed guidance, leaving many decisions for industry projects. Handling legacy systems and ensuring security and privacy are also unresolved issues. Effective reference architectures should address both general and local architectures, allowing components like machines and software systems to be autonomous yet integrated at runtime. RAMI 4.0, developed by German associations, provides a structured framework for implementing Industry 4.0, emphasizing standardization and integrating elements across layers, levels, and the product lifecycle. Its comprehensive approach enhances efficiency and innovation, guiding the transition to a more cohesive and interoperable industrial ecosystem.

To promote RAMI 4.0 in smart manufacturing, stakeholders should focus on several key areas. Firstly, the adoption of RAMI 4.0 should be encouraged to enhance interoperability and reduce technology fragmentation. Invest in training and education for engineers, managers, and technicians, and integrate RAMI 4.0 concepts into academic curricula. Foster collaboration between industry, academia, and government to refine the model through partnerships. Develop detailed implementation guidelines with case studies to assist companies. Prioritize interoperable systems by promoting standardized communication protocols. Support SMEs with resources, financial incentives, and technical assistance. Establish a feedback loop to update standards as technology evolves and encourage pilot projects to test and refine RAMI 4.0 in various settings. These steps will ensure that RAMI 4.0 supports current and future advancements in Industry 4.0.

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