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Identifying Reference Architecture Types for Stakeholder Groups in Industry 4.0

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Abstract. New developments in the area of the Industrial Internet-of-Things (IIoT) and Industry 4.0 offer huge potential for a more efficient and flexible industrial production, but are also accompanied by rising system complexity. Consequently, to deal with the increased system complexity, novel approaches, such as reference architectures, are emerging. However, most of these approaches are not yet mature and rather theoretical than ready-to-use. Thus, companies need to be provided with frameworks that actively support the transformation of their systems towards Industry 4.0. One of those frameworks has been introduced with Reference Architecture Model Industry 4.0 (RAMI 4.0), which counteracts the mentioned complexity and can be used for various use cases. However, as most of its concepts are too general to be applied directly to actual systems, the need for directly applicable reference architectures emerges. Therefore, this paper proposes a method to derive more detailed reference architectures based on RAMI 4.0 by making use of model-based systems engineering (MBSE), which target single manufacturing domains rather than the whole industry. Therefore, relevant stakeholders are analyzed and different types of reference architectures targeting their concerns are identified. The resulting reference architectures should be ready-to-use for interested manufacturers and thus, enhance the acceptance of RAMI 4.0 as well as improve systems engineering in industrial manufacturing. Finally, the developed reference architecture is evaluated in a proof-of-concept case study of a flexible production system.

Keywords. Reference architecture, Industry 4.0, RAMI 4.0, Model-based systems engineering.

Introduction

In the course of the fourth industrial revolution, production systems in various domains are getting increasingly complex. By integrating a large number of intelligent system components, new business models are emerging (Grabowska & Saniuk, 2022). For example, offering the possibility to produce individual products in lot size 1 and thereby maximizing customer satisfaction is one of those new opportunities (Javaid, Haleem, Singh, Suman, & Gonzalez, 2022). Moreover, the new automation potential reduces manual interventions in the manufacturing process and thus, increases productivity. So-called cyber-physical systems (CPSs) allow for decentralized decision making instead of high-level process management (Marques, Agostinho, Zacharewicz & Jardim-Gonçalves, 2017). However, as mentioned before, these changes result in an increased complexity and thus, hinder the manageability of current or future production systems. As a result, it is difficult for many companies to follow this trend toward Industry 4.0 and to update their production lines by implementing these new smart technologies. Having recognized this issue, several German associations introduced Reference Architecture Model Industry 4.0 (RAMI 4.0) (Hankel & Rexroth, 2015) to counteract the mentioned problems. RAMI 4.0 has originally been proposed to enhance standardization within the manufacturing area across multiple production domains. Additionally, the original implementation strategy suggests using the three-dimensional reference architecture as basis for systems engineering during the design phase of a production system (Bitkom, VDMA & ZVEI, 2015). RAMI 4.0 proposes three different dimensions, which classify a system and generate different viewpoints or abstractions. This leads to a better understanding of the individual system parts for various stakeholders and additionally contributes to a better understanding of the interdependence of the entire production network. A major technology driver to address stakeholders and to allow for them to express their knowledge in a single viewpoint is provided with model-based systems engineering (MBSE) (Mandel, Stürmlinger, Yue, Behrendt & Albers, 2020).

However, although providing such valuable concepts to counteract system complexity, it is still difficult to find actual industrial applications of RAMI 4.0. This might be due to the fact that the underlying standard is addressing multiple domains in a general way, but is missing specifications to be actually applied to a particular manufacturing system, as the concepts are too generic for instantiation (Binder, Neureiter & Lüder, 2021). Although being classified as a reference architecture per self-given denotation and falling into the criteria of the definition, companies fail to instantiate Industry 4.0-based systems with RAMI 4.0. On the one hand, suitable tools or methods to support this instantiation step might be missing, on the other hand, the need for a more specific reference architecture addressing only a single manufacturing domain becomes obvious.

This paper offers two major contributions. First, a detailed analysis of possible implementations of reference architectures in the industrial domain is given. Therefore, relevant stakeholders are selected and their interests in such system blueprints are evaluated. Based on RAMI 4.0, those interests are aligned with the three dimensions and adequate stakeholder clusters are constituted. For each cluster, the needed type of reference architecture is delineated. In addition, in the context of this paper, one of those reference architecture types is addressed in more detail, by making use of MBSE. A proof-of-concept on how such a reference architecture has to be designed to fulfill the stakeholder needs is described. In this example, the blueprint of the system architecture can be instantiated to function as basis for production in lot size 1 and thereby manage different options in the context of variant management. To evaluate the applicability of such a reference architecture for actual industrial application, an industrial case study is conducted.

The paper is structured as follows: in Related Work and State of the Art, an overview of RAMI 4.0, currently used reference architectures and their application in industrial projects in this area is given. The section Approach outlines the methods used for developing the reference architecture, while the following section delineates the implementation of a proof-of-concept reference architecture. The evaluation and application of the implemented reference architecture in a case study is described in the section Application. Finally, under Conclusion and Future Work the conducted study is summarized and an outlook provided.

Related Work and State of the Art

This section gives an overview over relevant topics for this paper. First an introduction to RAMI 4.0 is provided, then an overview over the current research on reference architectures is given and finally, related work on currently used refence architectures for industrial use cases is presented.

Reference Architecture Model Industry 4.0

RAMI 4.0 is a three-dimensional model containing all main aspects of Industry 4.0. It serves as framework for classifying Industry 4.0 technology and for illustrating the complex interconnections in industrial systems. RAMI 4.0 aims at generating a common understanding for Industry 4.0 systems and provides different stakeholder perspectives. As depicted in Figure 1 RAMI 4.0 consists of three axes: *Hierarchy Levels*, *Life Cycle & Value Stream* and *Layers*. The *Hierarchy Levels* axis is based on IEC 62264 (International Electrotechnical Commission, 2016a) depicting the different functionalities within a factory. In addition to the layers present in the so-called automation pyramid, the axis was extended by *Product* and *Connected World* to incorporate Internet-of-Things (IoT) and thus, adequately reflect Industry 4.0 systems. Based on IEC 62890 (International Electrotechnical Commission, 2016b) the *Life Cycle & Value Stream* axis illustrates the different states during the development and production process of production systems and products. The six interoperability layers of the *Layers* axis represent different aspects and features of the system (Hankel & Rexroth, 2015).

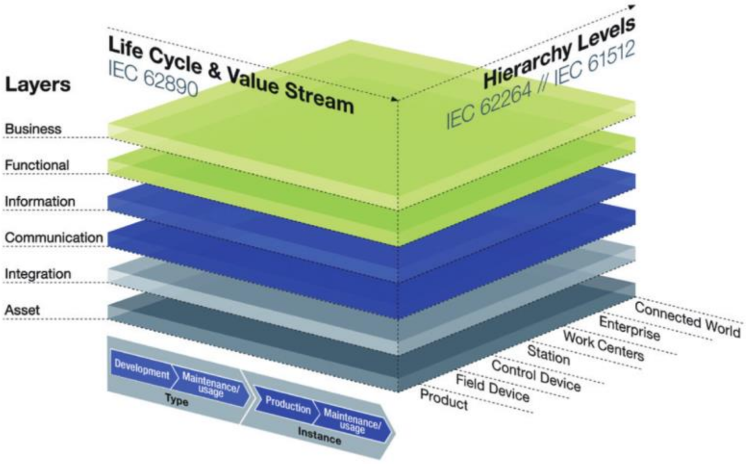

Figure 1. RAMI 4.0 (Bitkom, VDMA & ZVEI, 2015)

Reference Architecture

The term reference architecture is defined in many different ways. In essence, all these definitions describe reference architectures as a collection of knowledge and best-practices for developing system architectures in a given context or domain. On the one side reference architectures serve as architecture blueprint for new systems and on the other hand reference architectures promote standardization, therefore improving system quality and the architecture development process. To ensure the understandability of a reference architecture a common vocabulary for the given domain is used. Reference architectures can be categorized in various ways; it can be distinguished between high and low-level abstraction architectures, domain- and non-domain-specific architectures or single- and multiple-organization architectures for instance. Different types of reference architectures have been implemented in various domains, e.g., automotive, avionics or industrial production plants. Those implementations range from small-scale or single-organization reference architectures which are applicable for only a number of use cases to large-scale, multiple-organization architectures that are applicable for a larger set of companies or even a whole domain (Nakagawa & Oliveira Antonino, 2023).

When designing reference architectures, it is essential to initially define the intention of the reference architecture and to specify the requirements it has to fulfill. Therefore, a stakeholder analysis is the first step when developing the goal and vision of an architecture. Twelve possible stakeholders whose concerns have to be taken into account have been identified (Antunes, Barateiro, Becker, Borbinha & Vieira, 2011):

- Producer/Depositor: The entity responsible for the object to be produced;
- Consumer: The user consuming or accessing the produced object;
- Executive Management: Responsible for strategic decision making and monitoring the repositories;
- Repository Manager: Defines strategies and goals in the respective repository;
- Technology Manager: Responsible for all technological concerns to achieve the respective repository goals;
- Operational Manager: Ensures policy-compliant operation of the repository;
- Regulator: External entity responsible for monitoring the compliance with rules and legislation;
- Auditor: Responsible for monitoring the compliance with standards and regulations;
- Repository Operator: Business worker mainly concerned with upkeeping the daily business;
- Technology Operator: Responsible for the operation and maintenance of technical components;
- System Architect: Responsible for the design of the system architecture;
- Solution Provider: Entity providing components or services required in the system;

Reference Architectures for Industrial Use Cases

Reference architectures for developing software-intense systems have been successfully used in many companies as a blueprint and guideline. However, developing reference architectures for Industry 4.0 systems is more difficult, as those systems consist of multiple sub-systems and interconnected components. Therefore, specialized reference architectures need to be developed to cover the many different scenarios and use cases present in Industry 4.0 systems. Nakagawa, Antonino, Schnicke, Capilla, Kuhn & Liggesmeyer (2021) present six reference architectures currently used for industrial use cases. The reference architectures RAMI 4.0 and Industrial Value Chain Reference Architecture (IVRA) both provide an overview on how smart factories are structured on a high abstraction level. As described above RAMI 4.0 is a domain-specific architecture which aims at providing an understandable view of industrial systems for different stakeholders. IVRA provides information about the decomposition of smart factory systems and the combination of modules to achieve the manufacturing goals. While RAMI 4.0 and IVRA are rather abstract frameworks which can be used and extended in many different ways, the architectures Industrial Internet Reference Architecture (IIRA), Stuttgart IT-Architecture for Manufacturing (SITAM), LAsim Smart Factory (LASFA) and IBM Industry 4.0 are detailed reference architectures and may therefore be used for developing similar systems with little adaptation effort, however, for a narrower set of use cases. IIRA is a domain-independent architecture which serves as guideline for implementing IIoT. It contains architectural concepts as well as additional technical details concerning IoT system architecture. SITAM focuses on the integration and interoperability of smart factory systems and components. LASFA can be used to model the data flow between common Industry 4.0 systems, like Enterprise Resource Planning (ERP) or Manufacturing Execution Systems (MES). IBM Industry 4.0 mainly serves as decision tool, presenting a number of commercial solutions for different smart factory components.

Out of the six mentioned reference architectures, RAMI 4.0 and IIRA are the most frequently used ones, however, in most cases the reference architectures are customized or adapted to fit the respective use cases (Nakagawa, Antonino, Schnicke, Capilla, Kuhn & Liggesmeyer, 2021). To give a few examples, RAMI 4.0 was customized to incorporate IoT into an outdated manufacturing unit (Illa & Padhi, 2018) and in another use case extended to be used for modelling robotic arms (Lins & Oliveira, 2020). IIRA has been used to design, fabricate and test an industrial photovoltaic production system (Alonso-Perez, Cardenas-Maciel, Trujillo-Navarrete, Reynoso-Soto & Cazarez-Cazarez, 2022) and to describe an additive manufacturing system building upon the four viewpoints of IIRA (Hiller & Lasi, 2022). Although RAMI 4.0 and IIRA have been successfully adapted for industrial use cases, existing research provides limited guidelines on how to customize or extend the reference architecture models (Nakagawa, Antonino, Schnicke, Capilla, Kuhn & Liggesmeyer, 2021).

Approach

Engineering a reference architecture requires a systematic approach. For the reference architecture presented in this contribution a process called ProSA-RA was applied. ProSA-RA is an iterative process for designing and evaluating reference architectures. Before starting the engineering process, it is essential to define the intention of the reference architecture by considering the systems and stakeholders. The engineering process consists of three phases: architectural analysis, synthesis and evaluation. Firstly, in the architectural analysis phase all relevant information concerning the reference architecture is collected. This collected information might consist of existing architecture models, process descriptions, relevant standards for the domain, a set of stakeholders interested in the reference architecture or any other documents, books or knowledge relevant for developing the reference architecture's requirements. Secondly, in the architectural synthesis phase the architectural description is developed using architectural viewpoints, modeling languages and techniques of choice. Finally, in the architectural evaluation phase the developed reference architecture is evaluated for completeness, correctness, ease of use or against any other requirement previously defined for the reference architecture. To keep the reference architecture useful over time the three ProSA-RA phases need to be continuously revisited (Nakagawa, Guessi, Maldonado, Feitosa, & Oquendo, 2014). Figure 2 shows the adapted ProSA-RA process.

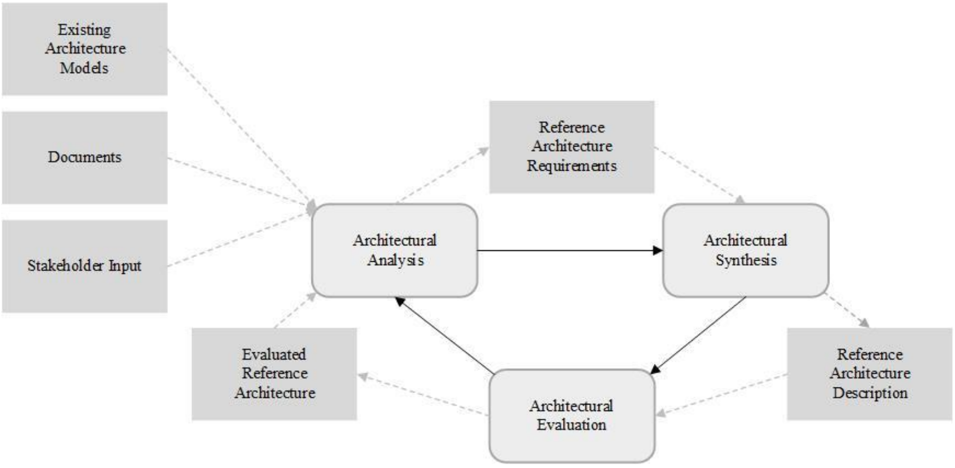

Figure 2. Adapted ProSA-RA process for developing reference architectures based on (Nakagawa, Guessi, Maldonado, Feitosa, & Oquendo, 2014)

In addition to the ProSA-RA approach, the theoretical concepts of Design Science Research (DSR) in information systems were used for this research. In DSR an artifact, in this case the identified stakeholder groups as well as the implemented reference architecture, are iteratively updated based on new insights from the environment as well as from an iteratively updated knowledge base. Especially in the manufacturing area, it is necessary, to consider the rapid rate of change, as new standards or technologies need to be promptly implemented. Moreover, when developing reference architectures, it is crucial to get regular feedback or new requirements from stakeholders or people in the industry (Hevner & Chatterjee, 2010).

Additionally, to the theoretical method DSR, the Agile Design Science Research Methodology (ADSRM), introduces an agile iterative approach suitable for the research area of engineering sciences. At the beginning of this iterative process a case study is defined. Based on this case study, the requirements the artifact to be developed needs to fulfill are developed. The artifact is then developed and implemented. Finally, the artifact is validated and the results are included in the next iteration of ADSRM (Conboy, Gleasure & Cullina, 2015).

In the context of this paper, using DSR and ADSRM, stakeholder groups and possible types of reference architectures are identified. Then, a case study based on the Siemens Fischertechnik model factory for producing plastic housings is defined. Based on this use case and the identified stakeholders and their needs a reference architecture is iteratively developed using the ProSA-RA process. The developed reference architecture model builds upon RAMI 4.0 as this high-level reference architecture framework provides a useful guideline on how to structure Industry 4.0 systems. The developed reference architecture serves as proof-of-concept implementation for the plastic housing production domain. The evaluation of the reference architecture is part of further research, as the developed reference architecture needs to be instantiated to be validated. The instantiation process as well as the resulting system architecture need to be evaluated.

Implementation

This section introduces the implemented concepts for developing the reference architecture. As RAMI 4.0 provides a useful guideline for classifying Industry 4.0 technologies and providing different stakeholder perspectives it is used as basis for the specific reference architecture development. Therefore, at first, the various system stakeholders are delineated and their interests and tasks in the context of RAMI 4.0 described. Subsequently, the second subsection provides suitable clusters of stakeholders, which result in various reference architecture types.

Stakeholder interests and tasks

In the following, the system stakeholders described above are outlined and a detailed analysis or their interests and tasks is given. The concerns of each stakeholder are described in a user story and the actual task in the context of RAMI 4.0 is outlined. To classify the tasks and sphere of influence of each stakeholder, the RAMI 4.0 matrix shown in Table 1 is used. This matrix consists of the two axes *Hierarchy Levels* as well as *Layers* (automation pyramid).

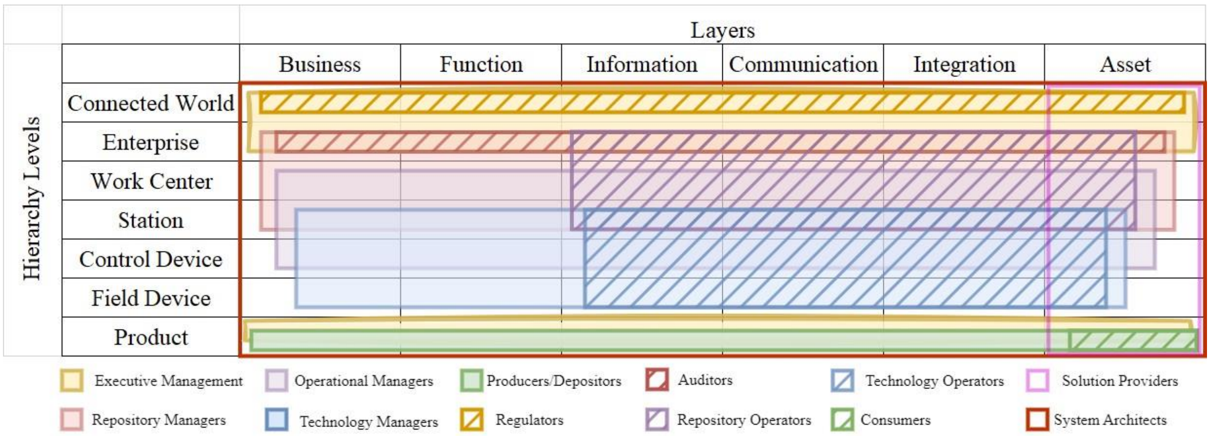

Table 1. RAMI 4.0 matrix for stakeholder classification

The hierarchy levels fulfill the design principle *separation of concerns* as each column deals with another aspect of the system, such as requirements, functions, or assets. The top-down arrangement of the matrix, the automation pyramid, considers the design principle *divide & conquer*. This makes sure that different abstraction levels are used, with some parts of the system being considered as black-boxes as well as white-boxes. In the following, each one of the stakeholders is classified within the matrix according to their area of influence in the system. This stakeholder analysis is an important step in the ProSA-RA approach, serving as input for the architectural analysis to iteratively develop a reference architecture.

Executive Management. The executive management is interested in high-level functions, business models and business processes. This stakeholder is the major decision-maker within the company and thus, is located at the highest two abstraction levels of the matrix (Connected World and Enterprise) and all interoperability layers (yellow box in Table 1). All requirements and decisions are traced to the lower abstraction levels and need to be considered there. Additionally, the executive management deals with the extension of product depth/broadness and thus is also located at the Product level (Product in Table 1).

Concerns of the executive management: As an executive manager, I want to implement business models, so that we gain profit/margin scheduled as planned with no cost overrun or reduction.

Regulators. Regulators do not have active influence in the production system. However, they need to be considered within the system context, as their external decisions may influence the system. Therefore, this stakeholder is located at the top of the matrix, the Connected World level over all interoperability layers (yellow dashed box in Table 1).

Concerns of regulators: As a regulator, I want to ensure compliance with regulations, technical standards, and laws such as environment, health and safety (EHS) regulations.

Repository Managers. The repository manager defines high-level requirements and functions for a particular segment of the company, like a factory or a department on Enterprise or Work Center level. In the context of RAMI 4.0 a repository is a functional unit like a department or a factory. Thus, this stakeholder is located between the Enterprise and the Station level (Enterprise, Work Center and Station), mainly acting at Work Center level and spans across all interoperability layers (red box in Table 1).

Concerns of repository Managers: As a repository manager, I want to define strategies, set goals and objectives for the repository, so that the repository meets the general company goals and sustainably achieves its intended purpose.

Auditors. Auditors need to assess the conformance of the company with regulations or laws and thus need tracing, lists of applied standards and rules and documentation amongst others. This stakeholder is located at the Enterprise level across all interoperability layers (red dashed box in Table 1) and evaluates the company at a high level.

Concerns of auditors: As an auditor, I want to evaluate or audit conformance with standards and regulations, so that the company certifies these standards and regulations throughout each life cycle.

Repository Operators. The repository operator takes the requirements and functions from the repository manager into account to find high-level technical solutions that fulfill business objectives, like deployment of factories or work units. Therefore, this stakeholder is not involved in the Business Layer or the Function Layer of RAMI 4.0, he only uses the results of those layers and acts on Information, Communication, Integration and Asset Layer. The repository operator is located on the same hierarchy layers as the repository manager (Enterprise, Work Center and Station), and mainly acts at Work Unit level (purple dashed box in Table 1).

Concerns of repository operators: As a repository operator, I want to ensure the correct execution of processes within the respective repository, so that the business and repository objectives can be fulfilled.

Operational Managers. Operational managers act as interface between technology managers and repository managers. They ensure continuous operation of the repository while meeting constraints set by technology managers. Their main tasks are the deployment and technical implementation of plants or machines; therefore, they act between Work Center and Control Device level (Work Center, Station and Control Device) and across all interoperability layers (purple box in Table 1).

Concerns of operational managers: As an operational manager, I want to manage an operational unit within a repository, so that the requirements of the repository are met and the single operations/functions are coordinated.

System Architects. System architects hold all parts of the system together, find corresponding interfaces and satisfy stakeholder concerns. This means that system architects are located on all levels (Connected World – Product) of the matrix across all interoperability layers (red border in Table 1). Their main goal is to ensure the interconnection between each of the panes.

Concerns of system architects: As a system architect, I want to design and update the architecture of the system, so that an overview of the entire system is given and the interfaces between system components and participants are defined.

Technology Managers. Technology managers need to consider high-level requirements and functions from repository and operational managers in order to reach goals or functionalities on a lower level, from Station to Field Device level (Station, Control Device and Field Device), across all interoperability layers (blue box in Table 1). Their area of responsibility includes machines or other control devices that execute manufacturing tasks.

Concerns of technology managers: As a technology manager, I want to manage the technological means within a repository, so that the system continuity is ensured.

Technology Operators. The technology operator needs to implement the functions designed by the technology manager from Station to Field Device level (Station, Control Device and Field Device), such as the technical implementation of a particular machine. This stakeholder is not located at the Business or Function Layer, as only technical aspects are of interest. The technology operator acts on Information, Communication, Integration and Asset Layer (blue dashed box in Table 1).

Concerns of technology operators: As a technology operator, I want to operate and maintain the components of the technical infrastructure, so that the system continuity is ensured.

Solution Providers. Solution providers offer solutions based on predefined requirements and a set of available options. In more detail, this means that only the Asset Layer of RAMI 4.0 is addressed, all other interoperability layers are not relevant for solution providers as they should already be given for the solution to be found. This stakeholder might span across all hierarchy levels of the matrix (Connected World – Product), as a solution can be found on different abstraction levels (pink border in Table 1).

Concerns of solution providers: As a solution provider, I want to receive the requirements for the components to be implemented in a comprehensible way, so that I can offer and implement the respective solution.

Producers/Depositors. Producers/depositors are responsible for the whole production of the end product; however, they cannot influence the production system. As far as RAMI 4.0 is concerned, only the lowest level, the Product level across all interoperability layers (green box in Table 1), is part of this stakeholder's influence. All specifications and technical decisions may be part of the tasks of producers/depositors.

Concerns of producers/depositors: As a producer/depositor, I want to manage and evaluate the design and production of a product, so that the final production plan of the product can be handed over to production.

Consumers. Consumers are only interested in using the resulting product and do not have influence on any developing steps. Only the last pane of the Asset Layer on Product level can be used by this stakeholder (green dashed box in Table 1).

The concerns of consumers are: As a consumer, I want to use the produced product, so that it fulfills my needs.

Identified types of reference architectures

Within this section, the previously defined stakeholders are clustered into groups, that are based on their concerns or tasks they fulfill. This leads to the establishment of five different types of reference architectures, that might be implemented to address each individual stakeholder. In the following, those five types are described in detail. The stakeholder type classification within the RAMI 4.0 matrix is displayed in Table 2.

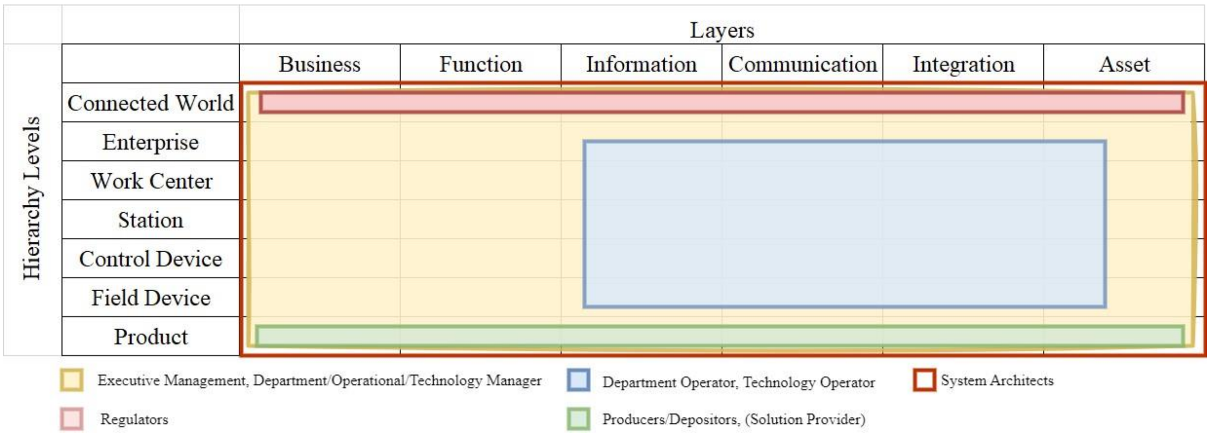

Table 2. RAMI 4.0 matrix for stakeholder types classification

Regulators. The reference architecture for this stakeholder type is a collection of all standards and regulations of a particular domain in form of requirements. This type of architecture is a prerequisite for the reference architecture of system architects. As they need to consider all standards or regulations within a particular domain. This reference architecture does not have to be company-specific and can ideally be used within the entire domain, such as automotive or steel production.

System Architect. For system architects, a reference architecture represents a collection of suitable concepts for a particular domain, which can be used during the instantiation of the system architecture. For example, the reference architecture inherits typical processes, requirements or plants that are used for the domain. It might also include various abstraction levels, as high-level processes could be decomposed into more granular ones, which are also representative for the entire domain and not company-specific. To summarize, the main goal of this reference architecture is the utilization of already established concepts within a particular domain for instantiating a new system architecture.

Repository Operator, Technology Operator. This type of reference architecture specifies all available technical resources in a specific plant or production facility. This means, all machines or manufacturing units, which could execute a large variety of production processes are part of the reference architecture. Whenever a new product should be produced in the production system, it can be evaluated whether the existing infrastructure is able to execute the new production process. In this context, skill matching is an important topic, i.e., matching the required skills from the new production process to available skills from the current production process. All in all, it can be said that this type of reference architecture can be used to evaluate the production of new products with available resources.

Executive Management, Repository/Operational/Technology Manager. A reference architecture for these stakeholders serves as baseline for deploying new factories or products. This type of reference architecture is derived from an existing as-is architecture and aims at reusing already established concepts within the company, while the context depends on the type of production and stakeholder. Additionally, it might provide multiple solutions based on established systems or processes which can be chosen when instantiating a system architecture. Shortly summarized, this type of reference architecture serves as basis for reusing concepts for a new production site with little effort, where already established concepts of the company might be applied.

Producer/Depositor, (Solution Provider). These stakeholders require a reference architecture for evaluating options for deploying different products or solutions. The reference architecture is a collection of available variants, that might be consolidated. The instantiated architecture is one particular variant. In the context of a 150% architecture, this type deals with the investigation of multiple possibilities. The 150% architecture is defined to provide all possible combinations of features for all the possible variants. Thereby, more information is modeled than actually needed for a specific product or system, which is also a major focus of the reference architecture. Thus, the goal is to provide variants based on customer requirements to supply a maximum number of customers with minimum effort.

Application

This section presents a proof-of-concept application of a stakeholder-oriented reference architecture. In the context of this research a reference architecture for one of the five identified stakeholder groups was developed. The reference architecture targets the executive management and repository/operational/technology managers. The developed reference architecture uses RAMI 4.0 as basis and builds upon the proposed high-level structure of Industry 4.0 systems. The reference architecture was developed following the ProSA-RA approach by iteratively including new information and stakeholder input. First, the case study based on a Fischertechnik plastic housing factory is described. Next, the developed stakeholder-oriented reference architecture is presented and finally the main findings are highlighted.

Case Study

The case study used for this paper is based on the Fischertechnik plastic housing factory provided by Siemens, depicted in Figure 3. The manufacturing process allows for producing one plastic housing at a time, with each plastic housing consisting of three components – a base, a lid and an insert. The plastic housings can be of various different shapes and forms, for instance the housing components can have a round or square outline and the lids can be plugged or screwed.

To achieve this flexibility the plastic housing factory consists of a gantry crane with two carriages, which can navigate the components between four processing stations in any order. Those stations represent two 3D-printing stations, a milling station and a grinding station. The base and the lid are manufactured on one or more of those four stations. After being processed by the stations the components are placed on the conveyor belt by the gantry crane and transported to the robot arm. The inserts of the plastic housings are processed on an alternative production path. These components are directly transported to a robot arm which places the insert on a punching machine. The robot arm also deals with the assembly of the individual components.

The manufacturing process is controlled using a Simatic S7-1515-2 PN from Siemens and a decentralized peripheral, consisting of a Simatic ET 200 SP module. Moreover, an HMI allows for selecting the required plastic housing variants.

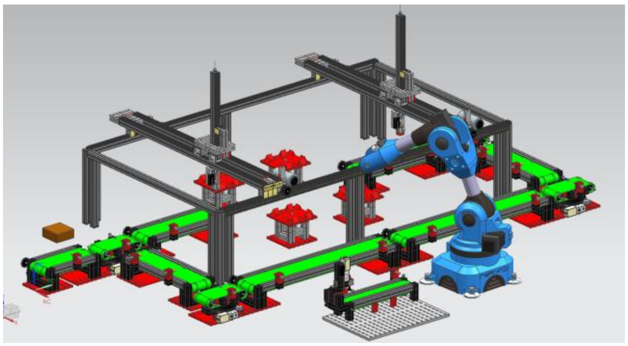

Figure 3. Fischertechnik plastic housing case study

Based on this case study a scenario was defined as possible use case for a reference architecture. In this scenario another Fischertechnik plastic housing factory must be built in a different location. The production process remains the same, however, the new site poses new conditions and constraints which need to be considered when developing the new system.

This simple case study serves as basis for a proof-of-concept reference architecture implementation. In order to fully evaluate the usefulness of reference architectures a more sophisticated case study needs to be evaluated in the future.

Reference Architecture Development from RAMI 4.0 Model

In order to develop a specialized reference architecture for the stakeholder group executive management and repository/operational/technology Managers, in a first step an as-is architecture of the Fischertechnik system was established. As defined in the ProSA-RA approach this as-is architecture is used as input for the architectural analysis.

AS-IS Architecture Model. The system architecture was developed based on RAMI 4.0 and exclusively describes the *Work Center* aspect of the RAMI 4.0 *Hierarchy Level* axis. The axis *Life Cycle & Value Stream* was omitted altogether from this architecture as type and instance management is not part of the defined use case. This results from two major factors. First, during engineering of systems and comparing concepts via the reference architecture, life cycle information is negligible. Second, the RAMI 4.0 *Life Cycle & Value Stream* axis mainly considers the life cycle of a product, as most components within the production system are solely utilized during the production phase. All in all, while this axis might be valuable for a complete system description with RAMI 4.0, the defined use case and reference architecture development might omit it. Apart from that, the model constructed extends over all *Layers* on *Work Center* level. The following paragraph provides a model description over all *Layers*.

Business Layer. On business level the system context of the Fischertechnik plastic housing factory, which is the system of interest for this architecture model, is defined. Raw material is delivered to the factory as input and the manufactured plastic housings are then passed on to the storage system. Moreover, the business case *Produce plastic housing* was identified, interacting with the two business actors, a factory owner and a production line operator. Based on the identified business case, requirements were derived. Among others, the identified performance requirements include processing more than ten components per minute and a service time under five seconds. Identified functional requirements are transportation from A to B as well as pick-and-place transportation and 3D-printing components, to give some examples.

Functional Layer. The functional elements 3D-print, transport, pick-and-place, turn, mill, grind, punch and assemble were modelled on this layer. Additionally, the input and output elements, as well as the interconnection between the functions was modelled.

Information Layer. The information layer describes the information exchange between the logical elements, which are the logical components performing the identified functions. For example, when delivering an object on the conveyor belt to the punching machine, some form of component data is communicated to the punching machine.

Communication Layer. On the communication layer the interfaces between logical elements are further specified. The interface *component delivered* for instance is used to notify the respective logical element.

Integration Layer. On this layer the logical elements which fulfill the identified functions from the function layer are defined. To give an example the logical element *Robot* was identified, which fulfills the functions *transport* as well as *pick-and-place*.

Asset Layer. The asset layer describes the specific components realizing the previously defined logical elements. In the context of this case study, the punching machine Fischertechnik Education is used as logical component *punching machine* to fulfill the function *punch*. A Kuka Robot was chosen for pick-and-place transportation and a Prusa 3D-printer is used to print the base and lid components to give a few more examples.

Resulting stakeholder-specific Reference Architecture

Based on the developed as-is architecture model and the stakeholder interests and concerns of the identified stakeholder group consisting of executive management and repository/operational/technology managers a specific reference architecture was iteratively developed following the ProSA-RA approach. This reference architecture should provide a blueprint and guideline for the selected stakeholders when developing a similar Fischertechnik plastic housing factory. As defined in the case study scenario the developed reference architecture should specifically aid in establishing a new factory in a different location.

In this scenario the production process of manufacturing plastic houses remains the same. However, as some requirements and constraints might change when building a new factory in a different location and possibly even a different country, the assets might be changed based on the respective requirements. Therefore, the developed reference architecture contains all process specific components from the as-is architecture and is extended by possible new requirements and additional assets that can be used in the new location. An overview of the reference architecture is provided by Figure 5. Please note that this image is not part of the constructed reference architecture, but is only a representative subset therefrom for visualization purpose. The larger box depicts the consistent part of the architecture, containing the functional elements, logical components as well as functional requirements. These elements remain the same when establishing a new factory at a different location. The smaller box above contains the capability-based variants. Desired requirements are matched to defined properties of possible assets, thereby giving an overview of which asset can help achieve which requirement. As highlighted in yellow in Figure 5, the assets in the reference architecture might not fulfill all of the defined performance requirements. In this example neither the robot Niryo One, nor the robot Kuka fulfill both performance requirements, i.e., processing more than ten parts per minute and providing a service time less than five seconds. In this case a placeholder named *Other* was included to point out the necessity for introducing a new asset to the factory or the failure to comply with all specified requirements. To give another example, highlighted in blue in Figure 4, the 3D printer Prusa used in the already established plastic housing factory cannot be shipped to the new location, therefore, 3D printer PolyJet might be a suitable option when building a new factory in a different location, as it can be shipped worldwide.

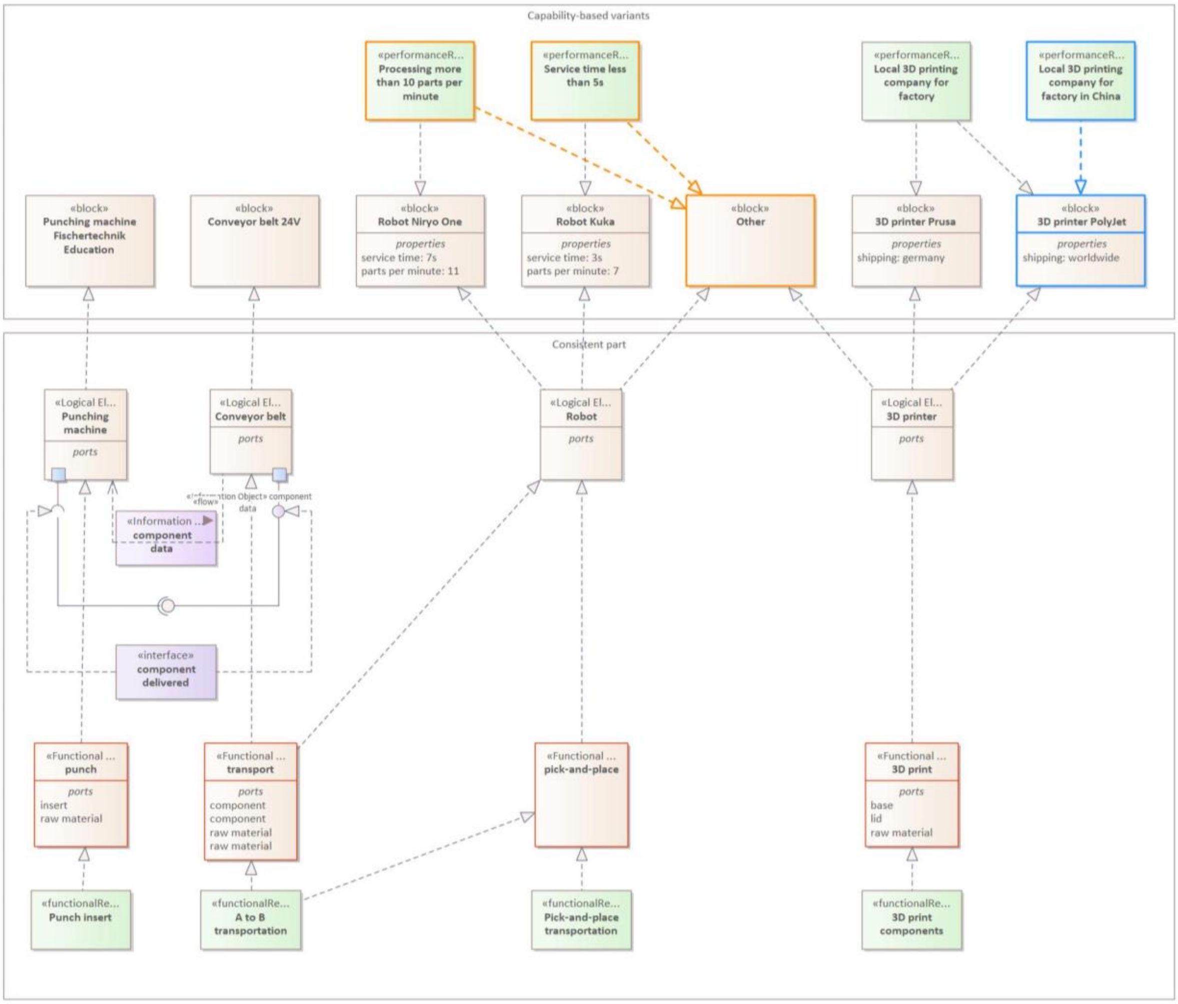

Figure 4. Reference Architecture Overview

Findings

Based on the developed reference architecture three main findings can be summarized. Firstly, a reference architecture based on an existing production process can be of great use when replicating the production process in a different location. The type of reference architecture presented above can be a suitable tool for the executive management and repository/operational/technology managers to make architectural design decisions for a new system. Secondly, using a reference architecture as basis for a new system architecture may save a lot of time and ensures system quality and consistency. Thirdly, reference architectures appear to be a suitable tool for managing different process or asset variants.

In this particular paper, it is not investigated how the reference architecture is utilized for instantiation or implementation of particular systems. The idea is that requirements engineering leads to the derivation of suitable requirements for a particular solution. Subsequently, the reference architecture provides logical or physical alternatives, which are selected via capability matching and applied in an instantiated system architecture. However, this needs to be investigated in further research.

Another aspect is that several stakeholder groups might have interest in the same type of reference architecture and thus be classified together. For instance, the reference architecture to be utilized by system architects or the executive management could converge or even be the same. This could also count for producers and technology operators, as they both rely on a 150% solution. As the research proposed in this paper mainly addresses one particular stakeholder group, distinguishing between multiple reference architecture types that address the same stakeholder groups is part of future projects and done with more sophisticated case studies.

Conclusion and Future Work

This paper proposes a method for deriving detailed reference architectures based on RAMI 4.0. Although RAMI 4.0 itself being a reference architecture, it has been shown recently that RAMI 4.0 is too high-level to be applied for many real-world manufacturing systems, as it addresses the entire manufacturing industry. Thus, specific reference architectures targeting particular manufacturing domains need to emerge. The method proposed in this paper aims to contribute to the following topics. As it is difficult to actually apply RAMI 4.0, although being standardized since 2016, the first goal is to increase its acceptance within the systems engineering community and enhance its applicability. Another contribution is to support systems engineering of complex production systems, which has become a difficult task due to an increasing number of intelligent components. By making use of a ready-to-use reference architecture, difficult tasks or decision-making could be strongly improved.

Different stakeholders and their interests in various types of reference architectures are outlined in section Implementation. Those stakeholders build the basis for developing different reference architectures, each addressing different concerns. This step is important to investigate needed reference architectures. The proposed reference architecture types for the identified stakeholder groups are summarized and described in detail in the remainder of the section Implementation. Consequently, section Application contains a proof-of-concept, which is based on a real industrial case study. While giving examples for all types of reference architectures, one particular type has been selected and evaluated in detail.

While the outcome of this work appears to be promising, several future research projects could be applied. For example, a more sophisticated case study might be more suitable for validating the resulting reference architecture and indicate additional benefits or limitations. In addition, as only one particular type of the identified reference architecture types has been technically implemented, an implementation of the other types is necessary to evaluate their concepts. Another project could use those reference architectures for applying variant management within flexible production systems, which would be a prerequisite for production in lot size 1.

Finally, another interesting aspect would be to investigate how the object-oriented systems engineering method (OOSEM) could be used to develop reference architecture models in an object-oriented way and compare it to the used ProSA-RA approach.

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