Utilizing an Enterprise Architecture Framework for Model-Based Industrial Systems Engineering

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***Abstract*—Accompanied by the fourth industrial revolution, current and future manufacturing systems are undergoing a major transformation. Driven by the integration of cyber-physical systems and the thereby resulting autonomy of its single components, organizing the interplay of its physical counterparts becomes more and more challenging. In order to structure and realize such an industrial system in a collaborative manner, the Reference Architecture Model Industrie 4.0 (RAMI 4.0) has been developed. However, although being widely accepted by the community, the standardized architecture is missing actual industrial applications. A major reason for this issue might be missing specifications in the standard itself, hindering the mutual development of such a critical infrastructure at the right level of detail. Thus, in order to counteract the mentioned problem, this work delineates the alignment of RAMI 4.0 with a well-established framework for specifying enterprise architectures, named The Open Group Architecture Framework (TOGAF). By coalescing the system development concepts of RAMI 4.0 and TOGAF, both of the approaches could benefit from each other. The result is thereby evaluated with an actual industrial case study.**

***Index Terms*—Reference Architecture Model Industrie 4.0 (RAMI 4.0), The Open Group Architecture Framework (TOGAF), Model-Based Systems Engineering (MBSE), Process Modeling, Industrial Internet of Things (IIoT)**

I. Introduction

Manufacturing companies are constantly faced with challenges in order to remain competitive. The uprising of technologies originating from the Internet of Things (IoT) and its industrial offshoot, the Industrial Internet of Things (IIoT), further substantiate this evolutionary process. One of the main goals resulting from the integration of such intelligent components into contemporary production lines is to sustainable transform those manufacturing systems into large-scale value creation networks [1]. By doing so, on the one hand a continuously changing market with a increasing demand for customized mass production and complex products needs to be satisfied [2]. On the other hand, remaining competitive in the long term is a major aspect to consider for most of the global players but also for the majority of small and medium-sized enterprisess (SMEs). Thus, iteratively adapting already established business processes to changing environmental factors is a difficult task, which will further bring traditional engineering practices to their limit [3].

In order to deal with the upcoming complexity in current and future manufacturing systems, several German associations developed the Reference Architecture Model Industrie 4.0 (RAMI 4.0) [4]. With special focus on the modeling paradigms *separation of concerns* as well as *divide and conquer*, the three-dimensional cube generates a foundation for mutual engineering of such industrial applications. Thereby, the main goal of RAMI 4.0 is to maintain and constantly adjust the Digital Twin representation of a physical system in order to consider all IIoT related aspects. While Model-Based Systems Engineering (MBSE) is the most promising approach to develop such a virtual counterpart on the basis of the reference architecture [5], [6], the number of actual practical applications is still marginal. A major reason causing this problem is considered to be the solely superficial specifications of RAMI 4.0 itself, which hinder the provision of a uniform development process.

Nevertheless, an already established and well-defined enterprise architecture framework has been published with The Open Group Architecture Framework (TOGAF) [7]. Originally defined for describing technical architectures, the standardized framework has become a leading approach when it comes to define whole enterprise architectures. By specifying a business-driven software architecture development process [8], TOGAF could be the right choice when it comes to modeling system architectures based on RAMI 4.0. This is furthermore underlined by the Model-Driven Architecture (MDA)-based top-down-arranged development process, which exhibits several parallels to the one of TOGAF. However, with regard to the latter, it has been pointed out that the architecture framework is missing practical application scenarios [9].

Thus, this paper provides two major contributions, outlining the advantages of the pursued approach. On the one hand, the missing specifications of RAMI 4.0, in particular the architecture definition as well as the development process will be defined in more detail by integrating the characteristics of TOGAF. This will allow a more sophisticated usage of MBSE for developing current and future industrial systems. On the other hand, the results of this work are going to provide an example of the usage of TOGAF to develop an actual industrial system. As this is currently under discussion [10], the applicability of this established architecture framework will be further enhanced.

The outcome is investigated with the help of a real-world case study, whose findings are discussed in the remainder of this paper, which is structured as follows: In Section II the related work about RAMI 4.0 as well as TOGAF and the state of the art of industrial systems engineering is outlined. The next section delineates the applied approach, while the architecture alignment is stated in Section IV. Subsequently, the applicability based on the industrial case study is demonstrated in Section V. Finally, in Section VI the results of the conducted study are summarized and a conclusion is given.

II. Related Work

A. RAMI 4.0

As explained in [11], the main advantage of RAMI 4.0 is the integration of several standards regarding automation. It includes the IEC 61512, the IEC 62890 as well as the IEC 62264, to mention some examples. In order to enable a global view on IIoT-based systems, the reference architecture model has itself been standardized in the German standard DIN SPEC 61345 [12]. Considering the different views of the three-dimensional cube, the main goal is to reduce the complexity while engineering systems within the industrial area. Thereby, the vertical alignment of RAMI 4.0 consists of different layers, each one addressing a specific aspect of the manufacturing system. The top-down arrangement of those layers is as follows: Business, Function, Information, Communication, Integration and Asset Layer. Each layer deals with separate considerations, as each term implies. Additionally, the two horizontal axes deal with the life cycle of the respective system component and their position within the automation pyramid [4]. However, a main criticism about the usage of RAMI 4.0 is stated in [11], which explains that the reference architecture itself is too complex and non-transparent to understand. This may be attributed to the rough specification within the official definition.

B. TOGAF

The Open Group originally proposed an enterprise architecture including a utilizable methodology as well as providing a corresponding framework. Better known by the term TOGAF, the standard has recently been published with version 9.2, as depicted in Figure 1. More precisely described in the Foundation Study Guide [7], the architecture consists of several modular parts.

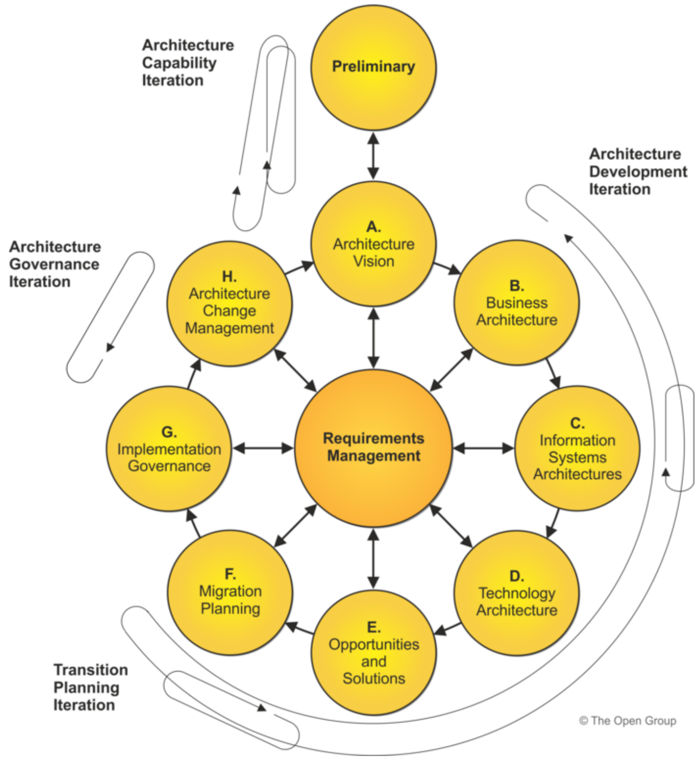

Fig. 1. TOGAF iteration cycles [13]

Requirements management is considered to be the most fundamental part of enterprise systems engineering, as it is located in the center of the development cycle. Nevertheless, a large number of parts deal with architecture development from Business to Technology and finish with planning the actual migration of the system. Furthermore, some parts deal with governing the architecture as well as planning new architectural adjustments. However, as the detailed process is explained in detail in IV, it will not be discussed any further at this point.

C. Industrial Systems Engineering

Industrial systems engineering with either RAMI 4.0 or TOGAF is not a completely new topic. There are multiple approaches trying to apply the mentioned methodologies in practical application scenarios. In contrast to novel approaches like AUTONOMICS for Industry 4.0 [14], which is especially focused on legal issues, TOGAF is well-known and already established within the industrial community. Thus, an example of how to use TOGAF is introduced in [15]. The author claims that enterprise architecture development practices usually differ from those mentioned in literature. That is why he introduced a practical case study explaining how to apply TOGAF and provide the results for researchers trying to adapt the theoretical methodologies in organizations. A similar approach, focused on the Enterprise Business Layer, has been proposed in [16]. A special feature of their work is the utilization of an AS-IS and TO-BE analysis for iteratively developing enterprise architectures.

As far as RAMI 4.0 is concerned, several approaches have recently been published trying to understand the implementation of the reference architecture for industrial systems based on case studies [17]–[20]. As most of these projects indicate the direction of future research, some other works have already had larger influence on the community [21]–[23]. However, as most of the mentioned propositions focus on trying to practically implement RAMI 4.0, it becomes obvious that the standardized reference architecture is missing formulations for actual industrial applications. Thus, the approach introduced in this work could solve this issue by integrating an established enterprise architecture as well as proposing a particular development process for models of current and future industrial systems.

III. Research Methodology

In information systems, research can usually be characterized by two different paradigms, behavioral science and design science [24]. While behavioral science deals with predicting human or organizational behavior, design science is the process of extending boundaries of capabilities by creating new methods and approaches. A typical example of such a novel methodology is the alignment of RAMI 4.0 with TOGAF. With the result of this work, industrial systems engineering can be taken a step further in terms of sustainability and better domain understanding by reducing complexity within this area.

In order to create such a new method, Hevner and Chatterjee [25] proposed a specific approach, the so-called Information Systems Design Science Research (IS DSR). With this approach, the authors introduce a particular framework, which indicates how to create such new processes or methodologies, so-called design artifacts. By deriving business needs or requirements from the domain and its surrounding environment, the development stage can be initiated. Thereby, already existing knowledge and established methods are utilized. During the development stage, the artifact is continuously refined and validated. Results are thereby applied in the appropriate environment as well as added to the knowledge base. In summary, in this paper the artifact to be developed is the refined reference architecture as well as the development process resulting from the interconnection between RAMI 4.0 and TOGAF.

However, while the development stage of IS DSR does not specify how to create the artifact evolutionary, the authors of [26] proposed an iterative development process, better known by the term Agile Design Science Research Methodology (ADSRM). By executing this methodology, short and simple iteration cycles are recommended. This results in quick construction and validation of developed components within each step of ADSRM. However, as each of the steps can act as entry point, usually the definition of a case study is a favorable way of initiating the development process. Therefore, this work makes use of a real-world industrial case study dealing with the copper-plating of metal plates.

A. Case Study

The company providing the use case is dealing with copper-plating of metal plates. Thereby, the plated through-hole technique is used in order to attach copper to the plates. The already successfully used manufacturing process is currently document based and the process capability of each production step is centrally managed. However, in order to adjust the company to the demand of Industry 4.0, the manufacturing system should be digitized. In order to execute this evolutionary development, a Digital Twin of the system has to be created based on the concepts of RAMI 4.0. This virtual representation is considered as reflection of the current production system, which is then adjusted to new IIoT-related aspects. At last, the actual system is migrated and the Digital Twin is again adjusted to the changes in the real-world system. As it might not be possible to implement all changes at once, an iterative development process has to be applied.

However, the following improvements for the current production system, which are implemented within the development process, are striven for and can be considered as requirements for the ADSRM-based artifact creation:

- Standardization across different production locations
- Fast and qualitative evaluation of customer requirements
- Increased quality and efficiency in production
- Automated program code generation using verified models

IV. Architecture Alignment

In order to utilize TOGAF for RAMI 4.0-based architectures, first the interconnection between the two standards has to be analyzed. This will enable iterative architecture development based on RAMI 4.0 and a further refinement of its architectural model. To do so, first the architectures are compared and mapped to each other in order to structure the intended approach. Then, the definition of a development process for creating Digital Twin representations of industrial systems needs to be elaborated.

A. Mapping

As both frameworks show several similarities, a bilateral mapping could solve the issue of interconnectivity. Thus, in Table I, the result of such a mapping is delineated.

While this representation acts as overview of the mapped architecture modules, a detailed description how RAMI 4.0-related concepts could solve the respective TOGAF phases is described as follows:

- Prelim: In the preliminary phase, TOGAF wants to identify stakeholders, creating architectural views and outlining a development process. This is done with the RAMI 4.0 standard itself and the process defined in [27], by falling back on the criteria of the ISO 42010.
- Requirements: The requirements are located in the center of the development cycle and must therefore be considered in each step. Thus, those requirements can be seen as the ones defined in each iteration step of ADSRM.

TABLE I
RAMI 4.0 IMPLEMENTATION OF TOGAF PHASES

TOGAF Phase	Implementation
Preliminary	RAMI 4.0 - DIN SPEC 91345
Architecture Vision	RAMI 4.0 Business Layer
Business Architecture	RAMI 4.0 Business Layer
Information Systems Architecture	RAMI 4.0 Function Layer RAMI 4.0 Information Layer RAMI 4.0 Communication Layer RAMI 4.0 Integration Layer
Technology Architecture	RAMI 4.0 Asset Layer
Implementation Governance	AS-IS System Architecture
Change Management	TO-BE System Architecture

- Vision: In the architecture vision, it has to be defined why the enterprise architecture is created. This is done in the Business Layer of RAMI 4.0, as defined in [27].
- Business Architecture: To support the vision, the business architecture has to be created. Thus, our approach specifies business process, context and requirement models.
- Information Systems Architectures: Those architectures can be realized with the Function, Information, Communication and Integration Layer of RAMI 4.0.
- Technology Architecture: Technological system components are derived from the Information Systems Architectures and are located in the Asset Layer of RAMI 4.0.
- Opportunities and Solutions: The selection of technical implementation scenarios based on the previously created architecture is currently done by the systems engineer, but research for automation potential with AutomationML is conducted.
- Migration Planning: The actual implementation of the system is the task of the respective project manager.
- Implementation Governance: Each implementation project has to be assessed and embedded in the Digital Twin representation within RAMI 4.0. In order to do so, an AS-IS architecture of the deployed system is created.
- Change Management: Based on new business cases or optimization potential, a new system architecture is created and the development cycle is initiated. This is denoted as the so-called TO-BE architecture of the industrial system.

B. *Process Definition*

The TOGAF Architecture Development Method (ADM), as illustrated in Figure 1, describes iterations for three different purposes. First, the development of a comprehensive architecture landscape by repeatedly iterating through the development cycle based on the general purpose of the enterprise architecture. Second, for enabling the creation of the actual system architecture on multiple views to address different stakeholder concerns. Third, the process of constantly evaluating the architecture based on change capabilities [13].

This is why an AS-IS and TO-BE system architecture development process has been integrated within the proposed approach. By implementing such a process, an iterative development cycle based on RAMI 4.0 can be utilized when evolutionarily developing industrial systems architectures. While the AS-IS architecture always represents a mirror image of the currently utilized production system, the TO-BE architecture indicates how new digitalization potential or Industry 4.0-related business cases can be implemented within this manufacturing system. A single iteration thereby deals with the execution of one specific business case by adjusting the system architecture based on the RAMI 4.0 cube. However, multiple iterations allow the development of the whole industrial system architecture by continuously integrating all optimization aspects. The practical application of this method is outlined in the next section.

V. PROCESS APPLICATION

The illustrated case study, as depicted in this section, validates the created development process. The model itself has been created with the help of the modeling software Enterprise Architect (EA) and the corresponding framework, called the RAMI Toolbox. In order to investigate the results in detail, the created case study model is publicly accessible[1]. The following abstracts describe the key points of the developed model and provide insights into characteristic process specifications regarding the proposed approach. Thereby, the description shows one particular iteration of the TOGAF development cycle, which serves as pattern for any other iteration run.

The iteration always begins with the AS-IS analysis. In order to find optimization potential or to implement new business cases, the system as it is used needs to be recreated. More specific, own model kinds for developing the Digital Twin of this production system have been utilized. In summary, a Context Model depicts the System of Interest (SoI) and its surrounding environment, business actors and interconnected systems, as depicted in Figure 2. This is done by applying the specifications of SIPOC, which is an acronym for suppliers, inputs, process, outputs, and customers. In the case of the copper-plating system, some input would be various kinds of energy, raw materials as well as engineering data. The finished metal plate is then transferred to the quality measurement department. The next step of this analysis is to model all business and manufacturing processes of the SoI. This will help with identifying shortcomings or ways for improvement. Thereby, the concepts of Business Process Modeling Notation (BPMN) and value-stream mapping, as shown in Figure 3, are utilized.

[1] A click-through model is available at http://www.rami-toolbox.org/UseCaseATS

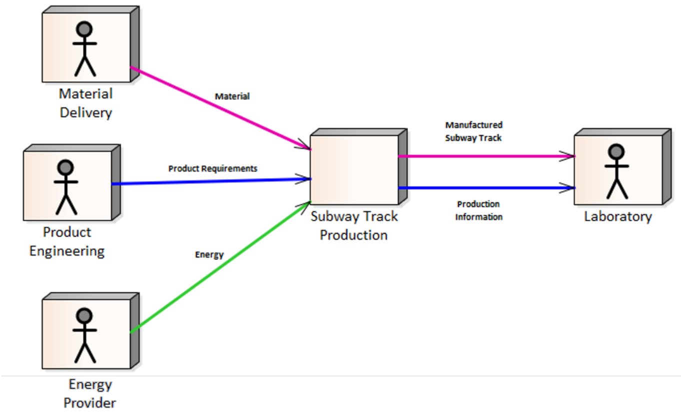

Fig. 2. SIPOC context diagram

Based on the results, the Business Layer itself can be described by identifying stakeholders with all business goals and the subsequent derivation of requirements. This is the point where the AS-IS architecture evolves into the TO-BE architecture of the system. Based on the identified business cases and requirements, the intended production system will be developed. Thereby, it is recommended to only implement one single business case for each iteration run. In the example of the copper-plating of metal plates, the chosen business case would be the digitization of the manufacturing process by automated program code generation. Thus, the needed IIoT infrastructure needs to be modeled according to the layers of RAMI 4.0. Some quantifiable requirements for this system To-Be would be a Total Effective Equipment Performance (TEEP) of more than 80%, faulty production of less than 10% as well as a First Pass Yield (FPY) of at least 95%.

Based on these requirements, the TO-BE Information System Architecture is developed. This is done by initially illustrating the desired manufacturing process with activity diagrams. By applying the Functional Architecture for Systems (FAS)-method, the specific Functions, the system has to fulfill, are developed and modeled according to black-box and white-box perspectives.

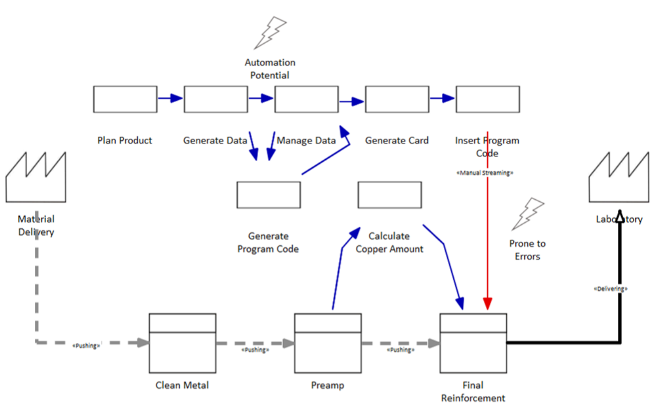

Fig. 3. Value-stream mapping diagram

As the application of this method is already described in other publications, it will not be addressed any further. In the exemplary scenario, some functions would be the measurement of borehole sizes, the selection of the correct parameters as well as the calculation of the amplification speed.

Subsequently, the specified functions are traced to actual system components as part of an MDA-based model transformation. Those components are used on the Integration, the Communication and the Information Layer of RAMI 4.0. A part of the Information Layer modeling process is thereby the specification of exchanged data as well as data model standards to further classify the data. The Communication Layer however deals with depicting the component's interfaces and the communication protocols or technologies. Last, on the Integration Layer, the used Information and Communication Technology (ICT) topology as well as Human-Machine Interfaces (HMIs) of the components are modeled. This layer furthermore includes all needed information to enable Industry 4.0-compliant interconnections. Going back to the case study, the OPC Unified Architecture (OPC UA) standard is used for ICT-related aspects, which include XML-based data representations as well as Ethernet as transport technology. Further details can be gathered from the published model.

At last, to implement the Technology Architecture, the chosen hardware components and technical specifications of the system are modeled on the Asset Layer of RAMI 4.0. This will provide the implementation basis for actually deploying the system. However, from the current point of view, this step has to be executed manually by the respective system engineers or project managers. After finishing the realization of the new system, the AS-IS architecture of the model has to be adjusted again. This will build the basis for further improvements or the implementation of new business cases. In the copper-plating system, this would be the automated transfer of the created program code to the Programmable Logic Controllers (PLCs) of the respective machines.

A. *Findings*

The approach outlined in this paper aligns the enterprise architecture development concept of TOGAF to the architecture definition of RAMI 4.0. By considering the results of the developed case study, it can be stated that the overall goal of incrementally evolving the system and its Digital Twin representation are feasible with the proposed approach. This can be substantiated by successfully implementing the changes to the currently used manufacturing system based on the architectural model. However, as only two iterations have been executed while validating the approach, a more sophisticated use case could exhibit further outcomes.

All in all it has to be said that industrial systems engineering based on RAMI 4.0 with respect to IIoT-based aspects is still in early stages. Although the introduced approach indicates how the three-dimensional layout could support the development of such systems, the architecture definition itself is still unspecified. Thus, further research projects should deal with refining this reference architecture regarding the ISO 42010.

VI. Conclusion & Future Work

RAMI 4.0 is considered to be one of the most promising reference architectures when it comes to developing Digital Twins of industrial systems. By providing different views and layers, complex automation systems can be structured and mutually developed to meet the stakeholder's concerns. However, from the current point of view, RAMI 4.0 itself might be too complex to understand due to missing formulations as well as practical application scenarios. Thus, this paper introduces an approach where the widespread and established enterprise architecture development framework TOGAF is used to enable MBSE of manufacturing systems according to RAMI 4.0. A major benefit of this interplay is the possibility to develop a Digital Twin model evolutionarily by constantly adjusting the actual system and its virtual representation. To do so, a specific architecture development process is proposed in Section IV, which illustrates the usage of each TOGAF phase to create current and future industrial systems in the best possible way. The results of this approach and its practical applicability have thereby been evaluated by a real-world case study, which is described in detail in Section V.

Based on the results of this work, a number of follow-up projects could be initiated. An example would be model-based code generation in order to also address the TOGAF phases "Opportunities and Solutions" as well as "Migration Planning". As these steps are mostly executed manually, automatically deploying code on PLCs could be the next step towards fully-automated model transformations, as required by MDA. Another project could be the architecture refinement of RAMI 4.0 itself, as an ISO 42010-based architecture description would refine the theoretical aspects of the reference model, which would further enhance its acceptance and usability within the community.

Acknowledgment

The support for valuable contributions of LieberLieber Software GmbH and successfactory consulting group is gratefully acknowledged. The financial support by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Research, Technology and Development and the Christian Doppler Research Association as well as the Federal State of Salzburg is also gratefully acknowledged.

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