Enabling model-based requirements engineering in a complex industrial System of Systems environment

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***Abstract*—The fourth industrial revolution resulted in the emergence of new ways for engineering production lines with the goal to optimize manufacturing processes by reducing expenses at the same time. This trend is mainly supported by the application of interconnected components, which are managed in a distributed way, as impelled by the Industrial Internet of Things (IIoT) or Cyber-physical Systems (CPS). While the complexity of these Systems of Systems (SoSs) is constantly rising, requirements engineering before actual implementing the system becomes increasingly difficult. Thus, comprehensive frameworks providing a foundation for model-based systems engineering, like the Reference Architecture Model Industrie 4.0 (RAMI 4.0) or the Software Platform Embedded Systems (SPES), have been introduced. Although providing a standardized methodology, missing formalizations impede the modeling of systems according to detailed architectural specifications. To address these issues, this paper introduces an approach for eliciting, specifying and managing requirements according to a particular process and aligned to architectural standards. In the end, the result is evaluated by a real-world case study. The outcome of this work will either verify the future system to develop by ensuring traceability or enable interoperability by dealing as a consistent reference point across viewpoints, systems or even domains.**

***Index Terms*—Requirements Engineering, System Architecture, Industrial Internet of Things (IIoT), Reference Architecture Model Industrie 4.0 (RAMI 4.0), Domain-specific Systems Engineering (DSSE)**

I. INTRODUCTION

Under the so-called umbrella term “Industry 4.0”, today’s production systems are undergoing a major transformation. Compared to the original production line, automation possibilities highly increased due to the integration of units that incorporate aspects originating from the Internet of Things (IoT). As a special demand for manufacturers is to remain competitive, new methods and technologies aiming to optimize production processes need to be integrated ahead of the competitors. Thus, the so-called Industrial Internet of Things (IIoT) is currently witnessing an upswing in terms of resource-optimized autonomous production, mainly promoted by self-communicating units making decisions on their own. These so-called Cyber-physical Systems (CPS) are geographically distributed system elements forming a complex value creation network, which is developed evolutionary and where decisions are made decentralized [1].

Taking this into further consideration, a contemporary industrial system not only represents a complex system, as defined in [2], it rather has to be considered as a System of Systems (SoS) [3]. This is either underpinned by the fact that CPS are systems themselves, which need to be engineered independently and with focus on their respective behaviors within the whole production line. As the increasing complexity in contemporary systems is not a completely new topic to discuss, several approaches providing frameworks for structuring accompanied by methodologies for developing such a system have been introduced [4], [5]. Thus, the standardized reference architecture Reference Architecture Model Industrie 4.0 (RAMI 4.0) [6] is considered to be one of the most promising methodologies for developing current and future industrial systems. However, this framework solely allows engineering of systems on one particular abstraction level [5]. The mapping between the RAMI 4.0 layers and the viewpoints provided by the Software Platform Embedded Systems (SPES) has enabled a more specific architecture definition. Moreover, in [7] it has been shown that the interconnection between the respective frameworks and their alignment enables cross-domain systems engineering. This is primarily done by considering the requirements viewpoint as reference point for providing consistency across all domains. Hence, RAMI 4.0 as well as SPES consider requirements engineering as entry point for initiating the engineering process and therefore provide a respective viewpoint for specifying those requirements on top of their layered reference architecture model. However, as both

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frameworks only address the frame to work in, the need for a more specific architecture definition in terms of requirements specification becomes clear.

As neither model-based requirements engineering for SoS [8]–[10] nor requirements engineering in the industrial area [11]–[13] are new topics to talk about, the contribution of this paper can be outlined as follows: The goal of the presented approach is to refine the Business Layer of RAMI 4.0 by the concepts of SPES in order to enable model-based requirements engineering of industrial SoS. Thus, with the aim to elicit, specify and manage requirements for IIoT based systems, a more detailed architecture definition than the theoretical concepts coming from RAMI 4.0 and SPES needs to be provided. To achieve this, already established standards, like the ISO 42010 [14], are utilized and integrated within the intended framework. The outcome thereby contributes to two propositions. On the one hand, a practical example of how to utilize the theoretical concepts of the Business Layer of RAMI 4.0 as well as the Requirements Viewpoint of SPES is proposed, which will enhance their usability. On the other hand, a comprehensive methodology for model-based requirements engineering of future industrial SoSs is introduced, serving as a basis for developing the technical architecture of such a system. The developed artifacts are thereby validated with regard to their applicability by making use of a real industrial use case.

To address these aspects, the structure of this contribution inherits the following sections: In Section II an overview of industrial systems engineering and requirements engineering is given. In Section III, the used development approach and the elaboration of the refined architecture definition is explained in more detail, whose applicability is demonstrated in Section IV. Finally, in Section V the results of the conducted study are summarized and a conclusion is given.

II. Related Work

A. Industrial Systems Engineering

In summary, RAMI 4.0 has mainly been developed by three German associations, *BITKOM*, *ZVEI* and *VDMA* [6]. Its goal is to enable the consideration of an industrial system based on domain-specific viewpoints. In order to do so, the architectural model is represented by a three-dimensional cube, each axis providing different aspects of the System of Interest (SoI). The vertical axis considers the life cycle or the value stream of such a system, while the horizontal one allows the structuring of components according to their application area as well as the hierarchical information exchange. The top-down integration provides a construct of six layers, each referring to a specific viewpoint of the system. For example, the Business Layer considers economical aspects, the Communication Layer protocols and infrastructures and the Asset Layer deals with enabling real-world representation of the system components.

Based on the reference architecture, several follow-up projects emerged. For example early approaches to utilize RAMI 4.0 and its associated Asset Administration Shell (AAS) have been made in [15]. In this work, the modeling of a digital twin according to specific standards and technologies has been addressed, which resulted in the introduction of a knowledge graph for integrating data in industrial interoperability scenarios [16]. However, as Model Based Systems Engineering (MBSE) is seen as a key enabler when it comes to developing a complex SoS according to the reference architecture, this kind of systems engineering is in the focus of contemporary research projects. To mention one example, the authors of [4] proposed an approach for modeling IIoT applications based on the Industrial Internet Reference Architecture (IIRA) and the Unified Architecture Framework (UAF) by enabling MBSE with the help of the Systems Modeling Language (SysML). A similar concept has also been introduced in [5], where a framework for tool-supported developing of industrial systems based on RAMI 4.0 is described in detail. By defining a Domain Specific Language (DSL) as well as a designated development process and a development environment in Enterprise Architect (EA), an extensive approach for applying MBSE in industrial systems engineering is proposed in this work. The results are thereby condensed and made applicable in a software called the RAMI Toolbox, which acts as foundation for the research conducted in this paper.

B. Requirements Engineering

Successful systems engineering needs to be based on a definition of system requirements, that is complete and free from errors. Especially the rising significance in systems with a substantial proportion of software requires efficient requirements engineering to ensure this. Requirements engineering describes the process of defining the key requirements of the SoI [17]. A key term of this process is the stakeholder. This term describes either a person or an entity represented by a person, who affects the requirements of the SoI directly or indirectly. During the requirements engineering process, the stakeholder needs are evaluated, documented and verified according to quality criteria. Every identified requirement needs to be documented appropriately. The resulting documentation should facilitate the communication between stakeholders as well as improve the quality of the documented requirements. Most commonly, natural language is used as form of documentation. An advantage of this approach is that the stakeholder is not forced to acquire a new form of notation. However, by using natural language there is also a danger that requirements are ambiguous so that information about specific requirements may become intermingled [18].

An alternative for language based documentation is a graphical approach. Requirements diagrams based on SysML, for instance, can be utilized to realize a model based requirements documentation. A benefit of this kind of documentation is that dependencies between requirements and other elements of the system can be visualized. For an appropriate realization of the identified requirements system elements are needed as well. Typically those elements are added to the model alongside with the relationships between these new elements and the respective requirements. Hence, traceability of the relationships between requirements and other elements of the system can be obtained [19]. Despite the abovementioned benefits, a requirements documentation realized by modeling a requirements diagram is not truly model-based. As outlined in [20] a requirement displayed in a SysML diagram simply depicts the textual definition of the requirement, however, the requirements are not captured appropriately. Rather a theoretical framework is proposed, in which requirements can be modeled as input/output transformations. The requirement in this case is considered as a system itself. Input and output are realized by interfaces for each requirement.

Generally spoken, it can be stated that model-based requirements engineering is considered to be an important factor when it comes to describe current or future systems. This is underpinned by numerous approaches introducing promising concepts. However, a big issue with the mentioned contributions is their generality. Being targeted to be applied in a large number of systems spanning various domains, only superficial aspects can be considered. Thus, with the industrial domain although being an area relying on well-defined requirements, the proposed approach builds on established methods with regard to requirements engineering. This will not only enhance the quality of RAMI 4.0 based models, but also lead to traceability between model and implementation as well as a more comprehensive systems engineering.

C. ISO 42010

The ISO 42010 [14] is an international standard that specifies concepts for the description of architectures of complex systems or software and gives a better understanding of its functionality and behavior. This standard is a common basis for the creation of Architecture Descriptions, Architecture Frameworks and Architecture Description Languages (ADLs). In this work, stakeholders and their concerns are elaborated to derive viewpoints as well as model kinds for the RAMI 4.0 Business Layer, as inferred from Figure 1.

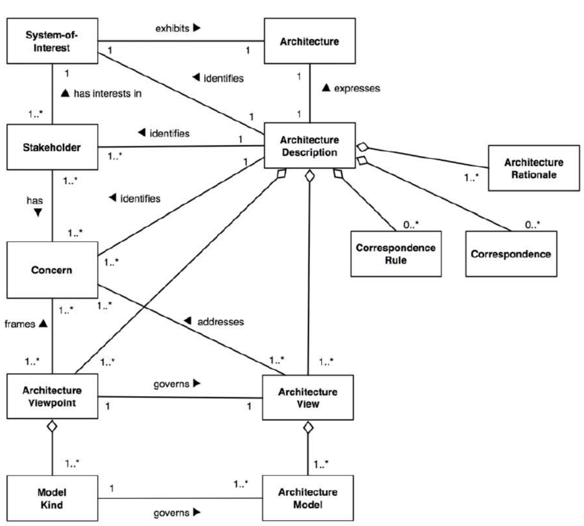

Fig. 1. ISO 42010 conceptual model [14]

The conceptual model thereby defines concepts to describe the architecture of considered SoIs, primarily to address stakeholder needs and to establish conventions for the creation of views for instance by using model-kinds. This standard defines only requirements for architecture descriptions, which can be used in proven modeling approaches, such as MBSE. Further Architecture Frameworks and ADLs are introduced as mechanisms for architecting. RAMI 4.0 is an example for such an architecture framework as SysML is an example for an ADL [14].

D. SPES

The SPES modeling framework is a generic architecture framework used for MBSE and thus for model-based development of systems. As the mentioned framework supports the modeling of multiple domains, inter alia the automation domain, it is suitable for system development in the context of industry. In particular, SPES not only meets the requirements but also the individual characteristics of systems belonging to this domain, like for instance CPS [3], [21]. Therefore, two essential approaches are specified by the core concepts based on fundamental principles defined in [22]: *Abstraction-Layers* as well as *Viewpoints*.These two approaches form a two-dimensional engineering space, where the horizontal axis is separated into four sections: *Requirements Viewpoint, Functional Viewpoint, Logical Viewpoint* and *Technical Viewpoint*. The vertical axis on the other hand represents different layers of abstraction. Thus, these concepts enable the modeling of systems from the very beginning, starting by the definition of requirements and evolving towards the final technical solution, under consideration of different system levels. A leading approach utilizing SPES for engineering collaborative embedded systems is thereby proposed in the running CrESt project[1], where a framework is created that allows the development of complex interconnected CPS [23]. Additionally, SPES is a key enabler for cross-domain requirements engineering including industrial systems, as outlined in [7].

III. IMPLEMENTATION

This section delineates the developed artifacts in order to contribute to the outcome of this paper. With the growing complexity in SoS architectures, it is important to follow a structured research process, which keeps a controlled overview of certain requirements and allows to react to changes during development. Therefore, the research methodology concerning this paper is based on the Agile Design Science Research Methodology (ADSRM) introduced in [24], as it is an agile approach and it provides a consistent workflow. The first input in regard to this research is an appropriate case study with the main focus on the industry domain. For this reason, a currently relevant topic discussed in a number of state-of-the-art projects, the industrial production of an Electric Vehicle (EV), is elaborated. Based on this case study, the iterative development cycle of ADSRM allows the evolutionary creation of new methods or technologies, defined as artifacts. In

[1]https://crest.in.tum.de/

this case, those artifacts are specified as: the interconnection between RAMI 4.0 and SPES, the development of a detailed architecture definition as well as an development process sketching how to develop an industrial SoS to the proposed architecture. In the following, the implementation of those artifacts is described in more detail.

As solely utilizing the established concepts of the Business Process Model and Notation (BPMN) to describe business models in such a complex domain would lead to losing important information for the subsequent Requirement Engineering, a domain-specific approach needs to be elaborated. Thus, the work in [7] deals with interrelations between certain Domain Specific Systems Engineering (DSSE) framworks, like RAMI 4.0, and SPES. The outcome yields that the only complete one-to-one mapping refers to mapping the requirement viewpoint of SPES either to the Business Layer or the requirement viewpoints of the examined state-of-the-art modeling frameworks. This mapping serves as a basis for further architectural specifications. The first step towards achieving this is to create an architectural foundation tailored to the peculiarities coming from the industrial domain. According to the ISO 42010, the respective stakeholders and their concerns can be addressed by one or more viewpoints. As the goal of this paper is to further refine the Business Layer of RAMI 4.0, the economical aspects of the SoI need to be considered during the system analysis, which is executed on this layer. Therefore, different concerns are taken into account for defining the viewpoints. One of those concerns is the interaction with other systems and the resulting inputs into the SoI or desired outputs from it. Furthermore, the user interaction as well as the runtime perspective of the system are of importance. Since the requirements engineer paves the way for the further system development, which is in this case conducted on the Function Layer, a specific viewpoint must be provided to address the abovementioned aspects. Therefore, the following views have been defined:

- Context View
- Business View
- Process View
- Requirements View

To give a detailed description and to further integrate ISO 42010 related specifications, each view is realized and made applicable by defining model kinds. As the business analysis is a difficult task altering from project to project, a set of available tools, integrated within a particular development process should be defined rather than a universal approach. Thus, in order to consider the context of the SoI, SIPOC has been integrated, which is a process for defining supplier inputs or outputs to customers. Furthermore, to model the system environment, the system context modeling language provided by Tim Weilkiens [25] has been included. The Business View is thereby usually applied with the help of a Unified Modeling Language (UML) Use Case Diagram, where Business Cases, Business Actors and their interests can be described, while the intended run-time process is illustrated with the help of the BPMN. However, to address the latter, domain-specific elements enabling the *Makigami*-method [26] or the so-called value-stream mapping [27] are also provided. Finally, the Requirements View is modeled using SysML Requirement Diagrams, but is not limited to it.

IV. APPLICATION

In order to evaluate the developed artifacts from Section III, as well as providing an example of how to execute model-based requirements engineering in an system, an overview of the modeled case study[2] is given in this Section. As previously mentioned, a real-world case study of an EV manufacturer is applied to create the architectural model. The advantage of this specific use case is that it provides insights into a SoS scenario with aspects from both, the Smart Grid and Automotive area. To further refine the EV production process as well as consider typical IIoT concepts, modular assembly lines including several production islands are used in order to dynamically produce each EV individually according to the desired specifications. Consequently, business models as well as the system context and the respective requirements can be derived from a production system that is actually applied in the industry.

According to the designated development process, the first step is to elaborate the system context. In this case the system is considered as a so-called user function by receiving input from suppliers as well as generating output for the customers. The SoI is thereby seen as a black-box, where information, matter or energy can be transferred. Following this concept, Business Actors like customers or the product engineering department provide information on how the car should be developed, while the suppliers deliver the material. Furthermore, the on-board charger or the Smart Grid itself provides energy to the car and thus have interest in business related aspects like electricity prices. As output, the EV obtains the energy while the customers are provided with the produced car as well as contract information. The goal of this model is to indicate the system context by showing what is send to the system and what needs to be delivered.

In the next step, the Business Analysis, the interaction with the SoI is shown by utilizing a use case diagram, as seen in Figure 2. In this model, previously elaborated Business Actors as well as additional parties having interest in the system are shown. Inside the SoI, different Business Cases are drawn, which indicate the separated application domains of the system. For example, the Business Case *Modular Assembly* is related to the industrial domain, whereas *Provide Energy Information to the Smart Grid* is considered to be an energy use case. The respective Business Actors are connected with the Business Cases to show their interoperability with the whole system or only a single part of it. Finally, the interests of each Business Actor are added to this diagram. This helps to find similarities or opposites and is a first step towards the requirements definition.

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

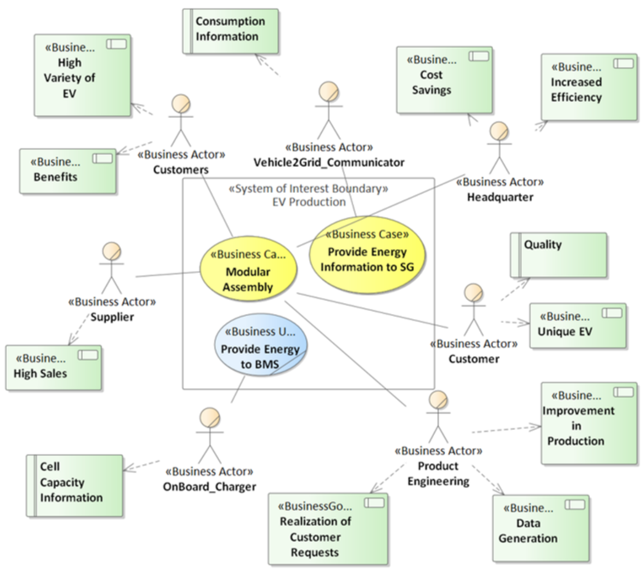

Fig. 2. RAMI 4.0 Business Analysis Diagram

As depicted in Figure 2, typical interests like cost savings, high sales or increased efficiency are desired by the Business Actors on the manufacturing side, while the customers demand a high variety of options, a reasonable quality as well as financial benefits. Additionally, in a SoS context, the on-board charger of the EV needs to have cell capacity information, while the vehicle-to-grid communicator needs to know something about the consumption.

Subsequently, the business process demonstrating how to achieve the single Business Cases is modeled on different abstraction levels with the help of BPMN. In this scenario, the Business Case *Modular Assembly* is shown in detail. Thereby, the process is initiated by a customer placing an order that includes unique specifications. Then, according to the Industry 4.0 vision, the respective production units are visited. More precisely, first the body shaping unit, the paintwork unit as well as the chassis unit are visited by the EV to produce. Next, after attaching all exterior, the propulsion of the EV is handled. This means, the electronics as well as the interior can be added to the body of the car, which is then finally assembled and checked towards quality issues. Modeling this single process can be repeated for each of the activities according to the desired granularity level.

After the black- and white-box perspective of the SoI has been enabled by modeling its in- and outputs as well as the business case interactions originating from the stakeholders, the actual requirements can be derived. This is done by summarizing similiar stakeholder interests directly into one requirement, as depicted in Figure 3. With the help of a requirements engineer and elicitation techniques, unique requirements can be determined. Furthermore, it has to be decided whether the identified requirements are explicitly from industrial nature or whether they are used as reference point for the interaction with other domains.

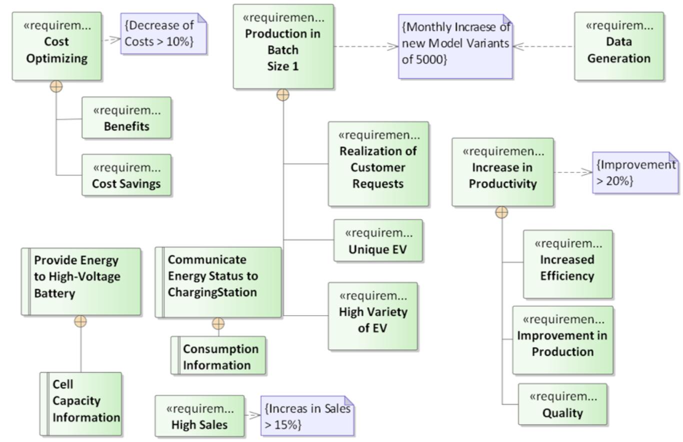

Fig. 3. SysML Requirements Diagram

For example, *Production in Batch Size 1* is an indisputable IIoT requirement, while *provide energy to high-voltage battery* is traced across domains, since it has to be considered in the Smart Grid area due to the energy demand, in the Automotive area due to its interconnection with other car parts and in the industrial area due to its need to be manufactured. Thus, by utilizing SysML, the requirements can be modeled and managed individually as well as a whole by making use of nesting-, trace- or derive-relationships. Based on the specified requirements, the functions of the SoI can be elaborated, whose explanation though exceeds the scope of this paper.

A. Findings

Using MBSE for a comprehensive requirements analysis appears to be a promising concept due to its versatility and the possibility to provide a common foundation for the involved stakeholders. However, the approach proposed in this paper shows that common MBSE methods exhibit shortcomings in terms of specificity when focusing on every facet of the industrial domain. For example, the BPMN provides a powerful set of tools for specifying business processes, but does not address particular manufacturing processes. However, as those processes inherit the most potential for transforming an original production system towards the concepts of Industry 4.0, a need for a IIoT-specific approach is given.

Accordingly, the contribution of this work can be summarized by delineating the results that were achieved trough an evaluation of the before mentioned case study. First, by providing different viewpoints, several aspects of the production system can be addressed in order to consider the needs of all stakeholders, no matter if they are originating from the system's context, the business processes or identified by a Kaizen Burst [26]. Additionally, by using SysML and thereby specifying different kinds of requirements, the traceability between the realized system and its model can be secured. More precisely, if a requirement changes, it can be traced which system components are affected and measures can be taken. Since the traceability is bidirectional, if a single part changes in the actual system it can also be retraced which underlying requirements are affected.

V. CONCLUSION & FUTURE WORK

Model-based requirements engineering in the industrial area is still a difficult task entailing a lot of different challenges to address. This is either encouraged by the increasing complexity of nowadays production systems or by the lack of existing tools or methods. Nevertheless, both referential modeling frameworks, RAMI 4.0 and SPES, consider requirements engineering as their entry points when it comes to developing the model of a system. However, their interplay and the resulting reference architecture provides a powerful method for developing industrial systems on their own as well as in a SoS context, which looks good on paper but is not well defined in terms of applicability at the current point of view. Thus this paper introduces an approach for model-based requirements engineering for industrial systems with the utilization of MBSE. In order to do so, first the previously mentioned reference architectures are analyzed in detail and their peculiarities are summarized for further refinements. The architecture for the Business Analysis Viewpoint is then elaborated in detail according to the ISO 42010 in Section III. Furthermore, with regard to requirement engineering methods, which are explained in more detail in Section II, a specific requirements elaboration process is also proposed by this approach, explaining how to elicit, specify and manage the requirements. The result is thereby evaluated with a case study addressing typical industrial aspects as well as SoS concerns, that occur with the development of an EV. While the feasibility was evaluated in this paper with a superficial use case in the first place, a more detailed elaboration has to be done in future projects based on a more sophisticated case study.

Based on the outcome of this paper, several follow-up projects can be executed. To mention some examples, after defining how to model the Business Layer of RAMI 4.0, a detailed description of how to develop the technical architecture of the system on the bottom layers needs to be introduced next. Regarding the SoS perspective, more research needs to be done in order to better understand the interoperability and interrelations within Automotive, Smart Grids or Smart Cities.

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