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Adapting an Agile Manufacturing Concept to the Reference Architecture Model Industry 4.0: a survey and case study

Abstract

Industry 4.0 architecture has been studied in a large number of publications in the fields of Industrial Internet of Things, Cyber Physical Production Systems, Enterprise Architectures, Enterprise Integration and Cloud Manufacturing. A large number of architectures have been proposed, but none of them has been adopted by a large number of research groups. Two major Industry 4.0 reference architectures have been developed by industry-driven initiatives, namely the German Industry 4.0 and the US-led Industrial Internet Consortium. These are the Reference Architecture Model Industry 4.0 and Industrial Internet Reference Architecture, which are being standardized by the International Electrotechnical Commission and the Object Management Group, respectively. The first research goal of this article is to survey the literature on Industry 4.0 architectures in a factory context and assess awareness and compatibility with Reference Architecture Model Industry 4.0 and Industrial Internet Reference Architecture. The second research goal is to adapt a previously proposed advanced manufacturing concept to Reference Architecture Model Industry 4.0. With respect to the first research goal, it was discovered that only a minority of researchers were aware of the said reference architectures and that in general authors offered no discussion about the compatibility of their proposals with any internationally standardized reference architecture for Industry 4.0. With respect to the second research goal, it was discovered that Reference Architecture Model Industry 4.0 was mature with respect to communication and information sharing in the scope of the connected world, that further standardization enabling interoperability of different vendors' technology is still under development and that technology standardization enabling executable business processes between networked enterprises was lacking.

Keywords: Industry 4.0, RAMI 4.0, Reference architecture, OPC UA, Industrial Internet of Things, Cyber-Physical Production Systems

1 Introduction

Industry 4.0 is expected to revolutionize, dissolve or flatten the automation pyramid architecture that has been established for several decades in the manufacturing industry [1,2,3,4,5,6,7,8,9,10]. This raises the question that what will be the new architecture to underpin Industry 4.0. A thorough survey of the scientific literature in Industry 4.0 identifies five paradigms that are being applied: Internet of Things (IoT), Cyber Physical System (CPS), Information and Communications Technology (ICT), Enterprise Architecture (EA), and Enterprise Integration (EI) [11]. The reader may get the impression that the Industry 4.0 Working Group did not define an architecture, since no such architecture emerged from studying the surveyed works. However, a Reference Architecture Model Industry 4.0 (RAMI 4.0) has been developed by BITCOM (the German Association for IT, Telecommunications and New Media), VDMA (Mechanical Engineering Industry Association) and ZWEI (German Electrical and Electronic

Manufacturers' Association) [12]. Since Germany is recognized as the leader for Industry 4.0 in Europe [13], it is to be expected that this architecture will become broadly established in the industry, at least in Europe. International standardization of various aspects of RAMI 4.0 relies on the IEC (International Electrotechnical Commission) [12]. Another major reference architecture is the Industrial Internet Reference Architecture (IIRA) developed by the US-led Industrial Internet Consortium (IIC), which is globally the main driver behind worldwide adoption of IIoT (Industrial IoT). IIRA standardization relies on the OMG (Object Management Group). An architecture alignment effort between RAMI 4.0 and IIRA is also underway [14].

Notable Industry 4.0 activity outside Germany and the US include initiatives in Japan, China, Korea and the UK. The Japanese manufacturing industry's IVI (Industrial Value Chain Initiative) [15,16] has defined the IVRA (Industrial Value Chain Reference Architecture); loose coupling between IVRA and RAMI 4.0 is presented in [17]. Unlike the German and Japanese Industry 4.0 efforts aiming at keeping or reshoring manufacturing jobs, the Chinese "Made-in-China 2025" plan aims to transition China from a low-wage manufacturing country to a technology leader [18] The Chinese have defined their own Intelligent Manufacturing System Architecture (IMSA) [19]; however, the country is very open to adopt German Industry 4.0 technology [3]. Currently RAMI 4.0 and IMSA are mutually recognized and alignment work has been undertaken [20]. South Korea is making a coordinated effort involving the technology, political, social and economic sectors [21,22]. The government led Manufacturing 3.0 project and Smart Factory Initiative can be seen as counterparts to the German Industry 4.0; however, since Korea's industrial focus is not on factory equipment or automation technology, there is openness to cooperate with and adopt technology from Germany, including RAMI 4.0 [3]. While the Industry 4.0 focus in Germany has a strong technology focus, the UK is recognized as a leader of the smart services aspect of Industry 4.0 [3,23]. Thus, the UK has been identified as a strong candidate for RAMI 4.0 adoption, especially due to the collaboration between the British Standards Institution (BSI) and the German Institute for Standardization (DIN) [3]. Common shared key characteristics between RAMI 4.0, IIRA, IVRA and IMSA include:

1. dissolution of the automation pyramid
2. a communication solution that makes data available to all parties in real time
3. the addition of a dimension that captures the lifecycle of the product and production facility
4. assets such as products and production resources have cyber counterparts

Many industrialized nations are not striving to be leaders in Industry 4.0, and their preparedness to adopt this technology is an important area of research. There are several possible perspectives to such research, depending on the current technological and economic situation in a particular country. In Brazil, [24] identified a subset of Industry 4.0 technology that the local industry is currently ready to adopt. A survey to members of the New Zealand Manufacturers and Exporters Association explored the general awareness of Industry 4.0 and perceived benefits, challenges and obstacles related to it [25]. Using India as their case, [26,27] have studied the possibility to adopt Industry 4.0 technology in a country which has not even properly exploited Industry 3.0 technology, namely computer-integrated manufacturing. [28] describes a Columbian education modernization effort to teach the practical skills required from engineers working in an Industry 4.0 environment. However, none of these works demonstrates explicit awareness for RAMI 4.0, IIRA or any other architecture with similar scope. Thus, the dominance of one or more reference architectures, the related standards and the standard compliant products and services is being established in the nations that are leading the Industry 4.0 revolution.

Due to the business power of the organizations behind RAMI 4.0 and IIRA, it is foreseeable that these architectures will gain extensive traction in the industry. Thus, the academic community may face great difficulty in attempting the technology transfer any architectures that have been developed without explicit regard to RAMI 4.0 or IIRA. Based on recent surveys that were made several years after the publication of these reference architectures, the large majority of the published literature is ignoring or unaware of them; instead, numerous paradigms such as IoT, CPS, CPPS (Cyber Physical Production Systems), EA, EI and Cloud Manufacturing (CM) are being studied by different communities of researchers [11,29]. In fact, RAMI 4.0 and IIRA could be considered to follow several or even all of the above mentioned paradigms, but the reverse does not hold: Industry 4.0 architectures inspired by these paradigms will not necessarily be compatible with RAMI 4.0 or IIRA. Thus, our first research goal is as follows:

> *RG1: to survey the literature on architectures proposed under the paradigms of IIoT, CPPS, EA, EI and CM in a factory context and assess their awareness and compatibility with RAMI 4.0 or IIRA.*

Any innovative manufacturing concepts will face an adoption barrier if they have not been developed and demonstrated on an industrially accepted reference architecture. However, it is currently difficult for researchers to avoid this situation. The body of scientific literature on Industry 4.0 remains 'non-consensual or ill defined' according to a recent survey [29]. More research is needed, which explicitly applies one of these reference architectures to a proposed Industry 4.0 manufacturing concept. Additionally, since Industry 4.0 technology and standards are evolving, the application of the technology is not straightforward for researchers and practitioners. Well documented proof-of-concept implementations will enable readers to gain the technical understanding needed to apply the lessons learned to their own applications. To this end, our second research goal is to apply one of these reference architectures to a previously proposed agile manufacturing method:

> *RG2: in previous work, a system for concurrent product design and assembly planning was proposed in a networked enterprises context, but the proof-of-concept was a single Java application [30]. In this paper, applications of RAMI 4.0 concepts and technologies to this system are demonstrated.*

2 Related research

In this section, research about Industry 4.0 architecture is reviewed. The review is grouped under the following categories: IIoT, CPPS, EA, EI and CM. Articles not mentioning these keywords will also be considered, for example an article about CPS in factory automation will be considered relevant even if the keywords Industry 4.0 and CPPS are not used. As per RG1, each of the reviewed papers is reviewed for awareness and compatibility with RAMI 4.0 or IIRA.

2.1 Industrial IoT

A disruptive development in Industry 4.0 and IIC's IIoT is the real-time availability of data to all users in the connected world. The RAMI 4.0 standard technology for this is OPC UA (Open Platform Communications Unified Architecture) and its counterpart in IIRA is DDS (Data Distribution Service). These will be discussed in more detail later in the paper, but it is notable that the major part of academic research on these technologies ignores three important points. Firstly, these industry driven initiatives are often not mentioned in articles. Secondly, the IIC is trying to appropriate the IIoT name. Thirdly, OPC UA has been developed by the archrivals of the industry consortium behind IIoT. A few examples are as follows: [31] proposes an IIoT architecture based on OPC UA. [32] proposes the Industrial Internet-of-Things Hub (IIhub) - OPC UA and DDS are mentioned but not used. IIhub covers part of the scope of RAMI 4.0 or IIRA, which are not mentioned. [33] evaluates the OPC UA as a core communication technology for IIoT frameworks.

Irrespective of the IIC, the academic community has done significant work on IIoT architecture. However, this work lacks coordination and researchers are not in agreement about how many layers the architecture should have and what are the names and functionality at each layer [34]. Several important aspects of IIoT architecture have been developed, but IIRA is not recognized and there is a lack of a common reference architecture to integrate these works. A few notable examples are as follows. [35] proposes an analysis framework for IIoT devices and a classification schema. [36] proposes an IIoT-based framework, which supports the definition, commissioning and operation phases of services in IPSSs (Industrial Product-Service Systems) for manufacturing environments. The impact of IIoT on business models for manufacturing companies is evaluated in [37]. The IIoT-related experiences of 76 companies help establish a framework with the key business model elements for the Industry 4.0 era – however, the support for business process automation in RAMI 4.0 and IIRA is not considered.

The lack of an established IIoT reference architecture has resulted in application developers being forced to develop home-grown solutions to common tasks that would ideally be addressed by standards-based technologies in the IIRA framework, which explicitly supports manufacturing and a number of other domains such as healthcare. Examples are as follows. [38] explores IIoT applications enabling product quality monitoring and providing data on machine utilization, condition monitoring and power usage. These applications are based on an IIoT-enabled machine-to-machine network using a stochastic embedding approach and parallel computing. [39] focuses on health monitoring applications of IIoT and defines a Healthcare IIoT (HealthIIoT) framework. Health-related data are collected by mobile devices and sent securely over the cloud to health professionals. [40] focusses on the advantages of low-latency 5G communication IIoT networks for covering the data transfer rate, data reliability and time-sensitive requirements of cyber-physical manufacturing systems (CPMS).

2.2 Cyber-Physical Production Systems

A central problem in CPS in a factory context is the standardization of data collection. Several authors propose web ontology language (OWL) ontologies for purposes including prognostics [41], decision support [42], digital twins [43], flawed data management [44], autonomous decision making for intelligent machines [45], open-knowledge-driven manufacturing execution systems [46], automating the engineering of batch process plants [47] and feeding data from the production process to the product design process [48]. This is in contrast to the RAMI 4.0 approach, in which an OPC UA address space would be defined and standardized as a companion specification [49]. [43] mentions RAMI 4.0 but does not recognize the role of OPC UA or describe in any detail how the proposed approach would comply with RAMI 4.0. Otherwise, the said authors do not mention RAMI 4.0, IIRA, IVRA or IMSA and thus they do not reflect on the implications of not following these architectures.

Numerous research groups have produced proposals for CPPS architecture. [50] proposes CPPS architecture design through 3 viewpoints: Implementation, functional and operational. [51] proposes a

5-layer architecture for CPS-based Industry 4.0 manufacturing systems. Based on an extensive CPPS literature review, [52] propose a Five-layer configuration architecture (Cognition-Configuration-Connection-Conversion-Computation). [53] proposes a multi-agent system architecture for CPPS with self-organizing and self-adaptive capabilities. Most CPPS architectures do not have an explicit lifecycle dimension as in RAMI 4.0, but the digital-twin shop-floor proposed in [54] is an exception in this regard. None of these architectures has any obvious mapping to RAMI 4.0, IIRA, IVRA or IMSA, and although the authors do not mention these reference architectures, the proposed architectures could be considered to cover a subset of the scope of these industry reference architectures. In contrast, the anthropocentric cyber-physical system (ACPS) reference model for factory automation [55] and the framework for operative and social sustainability functionalities in Human-Centric CPPSs proposed in [56] are fundamentally different from the said reference architectures due to the prominent human dimension. [2] demonstrate full awareness of the role of RAMI 4.0 and OPC UA, but a lack of awareness of Industry 4.0 Component Model, a key aspect RAMI 4.0 [12,49], so they propose a novel proprietary model vueOne to accomplish a similar purpose. Finally, [57] presents an expert discussion on how the CPPS concepts are mapped to RAMI 4.0 and how the industry is gradually migrating to this architecture.

Although IIRA has not been explicitly mentioned in any of the reviewed CPPS architecture related publications, its key technology standard DDS (Data Distribution Service) has been incorporated to some proposals. [58] proposes a CPPS architecture based on distributed databases using DDS as the communication solution; further works that assess and endorse DDS as the CPPS communication solution include [59,60]. Although IIRA is not mentioned in any of these scientific articles, DDS occupies a central place in IIRA similar to OPC UA in RAMI 4.0. However, the industry commitments to OPC UA and DDS by Industry 4.0 and IIC, respectively, are such that the RAMI 4.0 and IIRA architecture alignment working group suggests that both could be deployed to the same devices [14]. [61] performs a comparative evaluation of OPC UA and DDS after recognizing their roles in RAMI 4.0 and the US driven Industrial Internet (without mentioning IIRA).

2.3 Enterprise Architecture and Enterprise Integration

The top layers of RAMI 4.0 architecture, the 'business' and 'functional' layers, are expected to provide standard runtimes for executable business processes in the connected world [12], but so far there is a lack of standardization to this direction. In the area of enterprise architecture and enterprise application integration, much work on similar topics has already been done before Industry 4.0 related to platforms for eCommerce. These works could be categorized to web services-based approaches [62,63] and various competing XML schema-based standards such as universal business language (UBL), Open Applications Group Integration Specification (OAGIS), eXtensible Business Reporting Language (XBRL), XML Common Business Library (xCBL) and commerce eXtensible Markup Language (cXML) [64,65,66,67,68,69,70,71].

Only a minority of work in EA and EI explicitly mention Industry 4.0. [72,73,74] argue how EA meets the requirements of Industry 4.0 without proposing how traditional EA approaches could be extended to plant floor devices and automation systems. This trend of EA researchers to make claims in the area of Industry 4.0 while overlooking challenges resulting from integrating physical systems is identified and criticized by [35]. In contrast, [75] describe proprietary solutions for integrating EA to embedded systems, but acknowledge the lack of standardization in this area. [76] argues how properly designed EA can exploit the ability of expert workers to assess situations and make decisions, a concern that is central to Industry 4.0 although not obviously addressed by RAMI 4.0. EA research on Industry 4.0 may also clearly violate RAMI 4.0; for example [77] proposes extensions to the automation pyramid. None of the reviewed works on EA and EI demonstrate awareness on RAMI 4.0. Research on the 'business' layer of RAMI 4.0 is nearly non-existent and not affiliated with the entities involved in RAMI 4.0 standardization; [78] positions itself on the 'business' layer, but due to the lack of RAMI 4.0-specific technology standardization, resorts to using Business Process Modeling and Notation (BPMN) as will be done also in this article.

2.4 Cloud Manufacturing

The Cloud manufacturing concept was first proposed by [79] as a new manufacturing paradigm based on IIoT and advanced computing technologies. The main feature is the transformation of manufacturing resources and capabilities to services. A recent survey [80] does not mention RAMI 4.0, IIRA, OPC UA or DDS. Another recent survey [81] details the CM's community's original work on definitions, architectures, characteristics and previous case studies. [82] and [83] consider interoperability as a significant challenge for CM. [83] explicitly recognizes IIRA and RAMI 4.0 as standards-based solutions to this problem while [82] proposes an original service-oriented, interoperable cloud manufacturing system.

Several CM applications have been proposed, in which authors either propose original architectures or ignore architectural aspects. [84] proposes an architecture to support holistic quality assurance services. [85] and [86] propose cloud manufacturing-based scheduling services for dynamic collaborative manufacturing environments. [87] proposes a reliability assessment model of CM systems, assuming a service oriented architecture that is not specified in more detail. Agent-based manufacturing methods have been adapted to the cloud, aiming at advantages in virtual manufacturing cell formation [88] and improved performance in energy consumption, scheduling, resource allocation and real time data collection [89]. [90] propose a distributed blockchain-based architecture to handle the trust and security issues in a scalable manner. None of these works mention RAMI 4.0, IIRA, OPC UA or DDS, and authors do not offer any discussion about whether their proposal would be applicable in the context of such established reference architectures.

2.5 RAMI 4.0 specific work

This section concludes the literature review with a discussion of notable bodies of literature not related to IIoT, CPPS, EI, EA and CM. Over two hundred articles on OPC UA have been published by the IEEE, mainly in conferences of the Industrial Electronics Society. These include works on key Industry 4.0 architecture aspects such as service orientation for the industry [91], migration support for legacy systems [92,93,94], cloud manufacturing [95,96] and plug-and-play of components into a CPPS [97]. In addition to OPC UA, another key standard for RAMI 4.0 is the Industry 4.0 Component Model, which defines an administration shell for each component, permitting the interoperability of technology from different vendors. This standard is still in the early phases, but the concept has recently been used by several research groups to support their innovative Industry 4.0 proposals (e.g. [98,99,100]).

2.6 Functional requirements for system architectures in Industry 4.0

A current trend in system architecture design is advanced methods to address functional requirements. Functional changes may have major ramifications to software, electrical or mechanical aspects of the design, so new methods for co-design are proposed [101]. The use of early phase functional models has been proposed as a promising approach to overcome these issues before design proceeds to domain-specific architectures [102]. [103] point out the need to separate safety related aspects of complex cyber-physical systems architecture based on functional requirements to ensure that all safety relevant system parts are developed according to the relevant safety standard. [104,105] uses functional modelling for early phase assessment of mechatronic systems designs before proceeding to detailed domain-specific design. However, these works do not claim any explicit relation with Industry 4.0.

A few works claiming a link to Industry 4.0 have a functional requirements focus. [106] proposes a model-based approach for the engineering of production systems based on functional requirements. [107] proposes a functional requirements driven systems engineering methodology for retrofitting existing Computer Numeric Control (CNC) machines for Industry 4.0 plants. [108] presents a functional requirements driven testing method for validating Industry 4.0 service oriented architectures, taking into consideration the interaction of distributed functions. [109] discusses functional requirements driven virtual commissioning of Industry 4.0 systems. However, all of these articles only claim a link to Industry 4.0, without detailed discussion of prior work on Industry 4.0 architecture in general or RAMI 4.0 in particular.

It is notable that RAMI 4.0 is not explicitly motivated by considerations related to co-design of complex cyber-physical systems or opportunities arising from effectively exploiting functional requirements of such systems. Rather, the 4.0 refers to 'Fourth industrial revolution', in which the idea is to augment existing physical facilities with information and communication technology to make information available in real-time across all hierarchy levels and lifecycle phases [12]. Functional requirements are not prominently addressed in RAMI 4.0. There is a 'functional' layer in RAMI 4.0, but its purpose is to provide business process automation [12], and thus it is not addressing the concern of managing functional requirements in complex cyber-physical systems. In conclusion, although some authors use the terms Industry 4.0 and CPS without making a clear distinction between them, the works reviewed in this subsection show that there are two different bodies of literature. One useful distinction to make would be if the work targets green-field or brown-field projects. Green-field projects, in which there are no constraints imposed by prior work, are strong candidates for functional requirements driven architecture design methods, which optimize the interactions between physical and cyber components. Brown-field projects such as plant renovation for Industry 4.0 are constrained by the need to adapt to existing physical facilities and plant-floor automation systems, in which case the RAMI 4.0 architecture can be helpful.

2.7 Future directions

The potential benefits of Industry 4.0 are currently only beginning to be realized. This literature review is concluded by pointing the reader to recent surveys addressing key developments to be followed over the next years. Firstly, despite ongoing work with RAMI 4.0 and IIRA, standardization remains a major challenge [110]. Disruptive developments are anticipated from artificial intelligence exploiting big data, so the Industry 4.0 systems' ability to generate and manage big data [111] are critical for achieving the potentials of artificial intelligence. Finally, the literature on EI and EA is only beginning to investigate the possibilities of IoT [112].

3 System concept

In this section, RG2 is addressed. In [30], a system and method for concurrent product design and assembly planning was proposed. While the research was motivated by a scenario involving several organizations, the UML (Unified Modeling Language) descriptions of the proposed system and method, as well as the implementation as a single Java project, require further work on how the method could be applied across organizational boundaries. This is the first step towards addressing RG2, and an overview is presented in Figure 1.

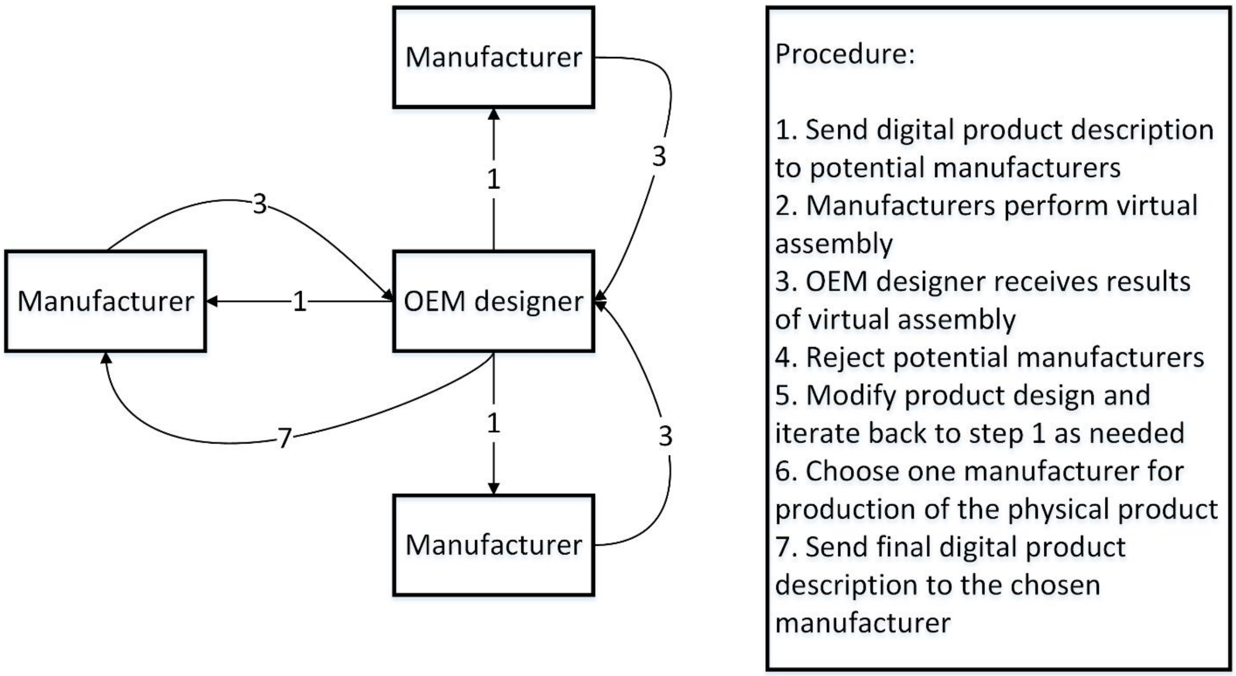

Figure 1 Concurrent product design and assembly planning in a networked enterprises concept

The next step towards addressing RG2 is identifying how the procedure in Figure 1 can be mapped to RAMI 4.0. Figure 2 shows the 6-layer RAMI 4.0. The layers that this article focusses on are highlighted in orange. The procedure in Figure 1 crosses the hierarchy levels “Enterprise” and “Connected world”. The steps 1-6 in Figure 1 belong to the “Development (Type)” phase of the RAMI 4.0 product life cycle. They are done entirely in simulation and aim at improving the product design from the product assembly perspective. Step 7 in Figure 1 marks the transition to the “Production (Instance)” phase of the RAMI 4.0 product life cycle.

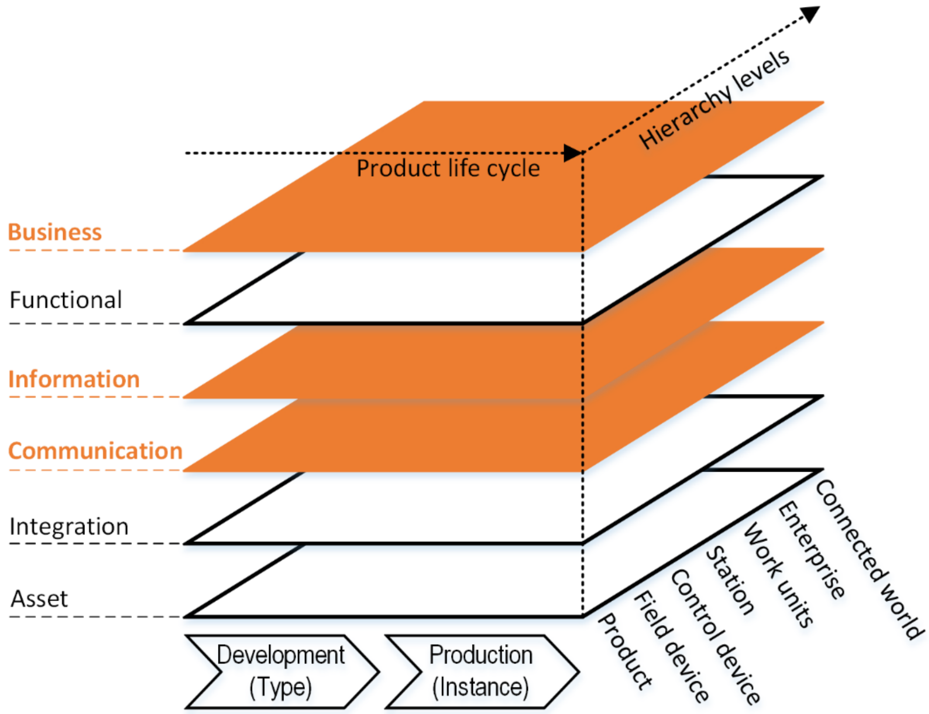

Figure 2 Reference Architecture Model Industry 4.0 adapted from [12]. This article focusses on the layers that are highlighted in orange.

The next step towards addressing RG2 is identifying how the procedure in Figure 1 can be split between the RAMI 4.0 layers. In the business layer, the business processes are defined and especially links between business processes in different organizations are established [12]. This has been done with BPMN (Business Process Model and Notation) in Figure 3. As opposed to Figure 1, in which the procedure is illustrated with three manufacturer candidates, Figure 3 shows only one manufacturer candidate, to reduce clutter. An arbitrary number of candidates is possible, and identical communication is conducted with each candidate. This diagram shows the key aspects of the process and further work may focus on details such as negotiation for price, lead time and throughput. The horizontal sections are pools, not swimlanes, meaning that they cross organizational boundaries, in which case messages (dotted arrow) are sent. In terms of RAMI 4.0 hierarchy levels, each pool is at the “Enterprise” level, and the entire BPMN is at the “Connected world” level. From left to right, the progression in Figure 3 corresponds to the Value Stream dimension of RAMI 4.0 as follows. The Virtual assembly corresponds to RAMI 4.0 Development (Type). Physical assembly corresponds to RAMI 4.0 Production (Instance).

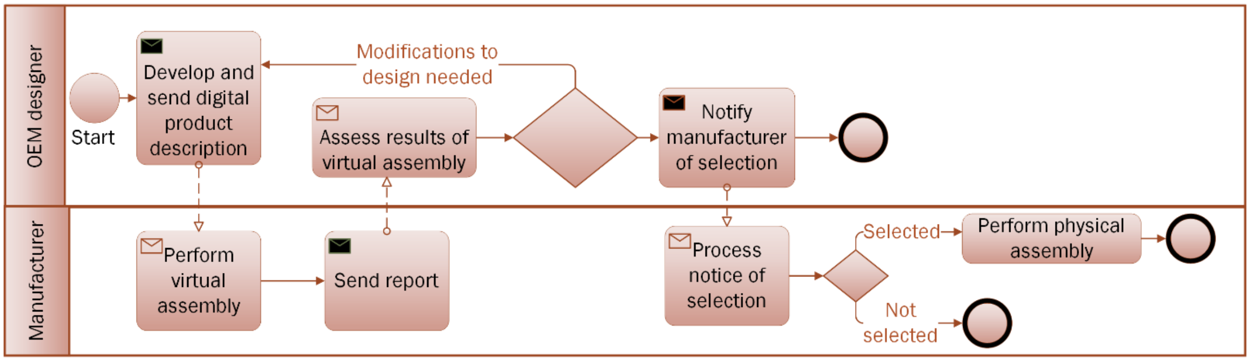

Figure 3 Business processes defined on the "Business" layer of RAMI 4.0

The next step of addressing RG2 is to refine the business process in Figure 3 to the other layers of the RAMI 4.0 in a general way that avoids proprietary solutions. Looking at Figure 2 and moving down from the “Business” layer, next is the “Functional” layer. The functions that comprise the business processes are formalized on this layer, so that they can be executed on a runtime that enables horizontal integration of the functions across organizations and organizational units [12]. However, at the time of writing this article, this layer of RAMI 4.0 is not yet mature, so this layer shall be addressed in further research. Moving down one layer brings us to the “Information” layer. Here the content of the information to be exchanged is defined in a machine readable and non-proprietary way. The standardized technology for this purpose is OPC UA (Open Platform Communications Unified Architecture), and especially its mechanism for defining address spaces [49]. In this article, the relevant information content is the digital product description, for which an OPC UA address space will be defined below. The next layer is the ‘Communication’ layer that allows any entities to exchange the necessary information in real time. In this article, the communication between the OEM and manufacturers (step 1 in Figure 1) is implemented as OPC UA client-server communication. At the time of writing, OPC UA is the only technology available for realizing the ‘Communication’ layer [49].

In this article, the two lowest layers of RAMI 4.0 were not addressed, since the scope of this research is to apply the manufacturing concept in [30] in a simulation environment without addressing all the details related to integrating technology from several vendors. These details should be addressed on the “Integation layer”. The application of OPC UA is a partial solution to this problem, but the application of the Industry 4.0 standard Component Model is also required [49]. This is an important area of further research.

In the remainder of this section, RG2 will be addressed in more detail regarding the development of an OPC UA address space on the “Information layer”. Figure 4 shows the OPC UA reference type hierarchy and our extensions to it in orange. With these reference types, it is possible for the OEM to construct the kind of digital product description used by the agile production cell proposed in [30]. This cell is capable of performing automatic assembly planning based on this description. This capability depends on part types such as CAD models being augmented with coordinates of connection points as well as connections between connection points of two parts to be assembled. The two orange reference types in Figure 4 are used for this purpose.

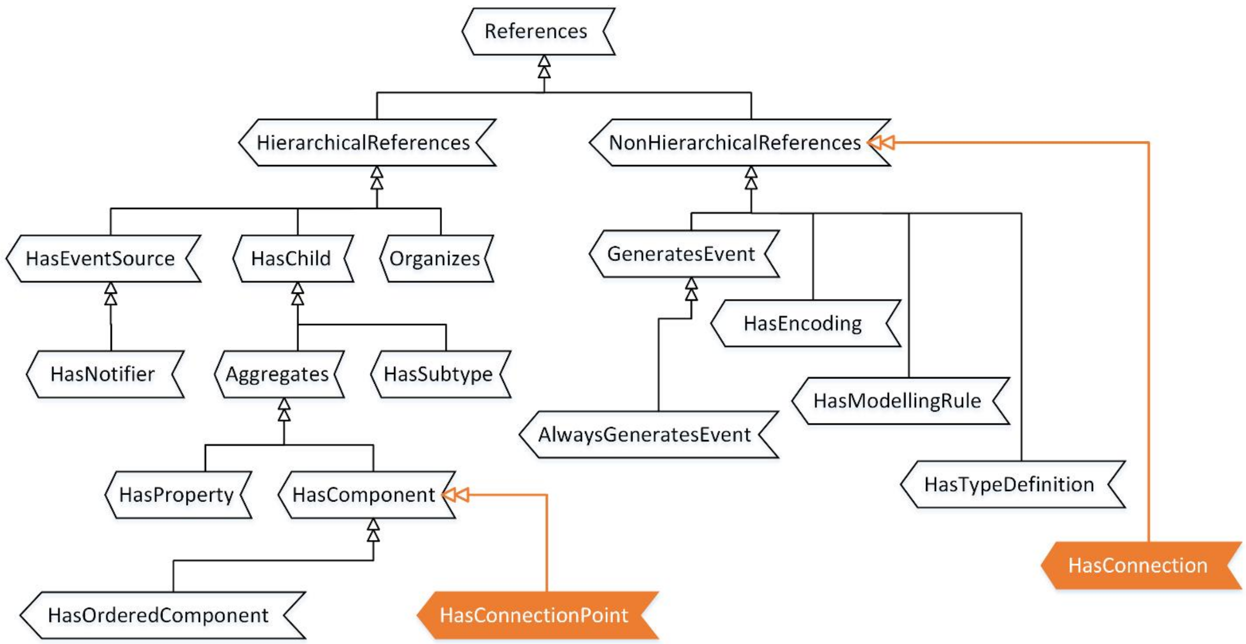

Figure 4 Extensions to OPC UA reference type hierarchy. Extensions are in orange. Adapted from [113]

Figure 5 shows the OPC UA address space that was defined. [30] presents an automatic assembly planning capacity for digital product descriptions consisting either of CAD parts or of lego blocks. In case of CAD parts, the capacity is mainly relevant for parts that can be assembled in top-down fashion. The industrial applicability for the research with lego blocks was limited to certain toy manufacturers, but certain ambitious research ideas could be demonstrated with these simple part types. In particular, with 30 square or rectangle lego blocks, a virtually unlimited number of assemblies can be defined. The method in [30] was able to perform automatic assembly planning for a large subset of them, including collision detection and connecting a part to the assembly from below.

This idea of defining digital product descriptions from CAD components and lego blocks is formalized in Figure 5. The product is an instance of “DigitalTwinType” defined in the top right corner, i.e. the “DigitalTwin” object. This name is due to the concept proposed in [30], in which a digital twin is generated from the digital product description. The twin then orchestrates the production resources to manufacture the product. In this case, the control software of the production resources does not have any hardcoded logic about what kind of product is being assembled, resulting in a highly versatile assembly cell. The twin consists of several parts in a folder called “Parts”. At this point, especially readers with background in UML should appreciate that in an OPC UA address space, type and instance definitions are mixed. Thus, Figure 5 should not be read as an UML class diagram consisting of type definitions only. The content of the “Parts” folder is specific to the digital product description of a specific product. The rest of Figure 5 is a general framework that can be used to define any product instance consisting of the said part types: CAD parts, square lego blocks and rectangle lego blocks. To reduce clutter, the diagram omits the rectangle lego type definitions and subtype definitions of “CadPartType”.

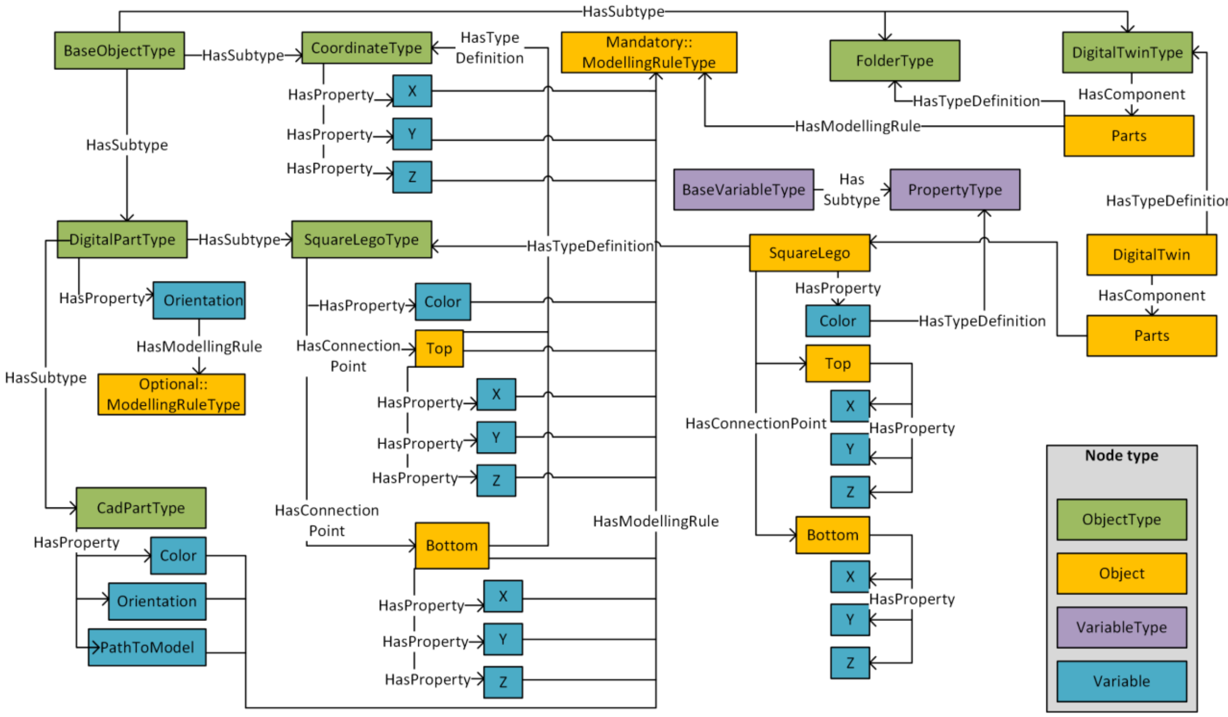

Figure 5 OPC UA address space defined using reference types in Figure 4

The final step in addressing RG2 is to actually define a digital product description in the OPC UA server address space. To reduce clutter in Figure 5, only one “DigitalTwin” object is defined, so only one digital product description is present on the server. In the “Parts” folder, only one “SquareLego” object is included. Figure 6 shows an excerpt of an OPC UA address space that complements Figure 5 with the one digital product description. To keep the diagram readable, the product is very simple: a lego tower consisting of four square lego blocks one on top of each other. However, more complex products have been defined and will be discussed further in the remainder of this section.

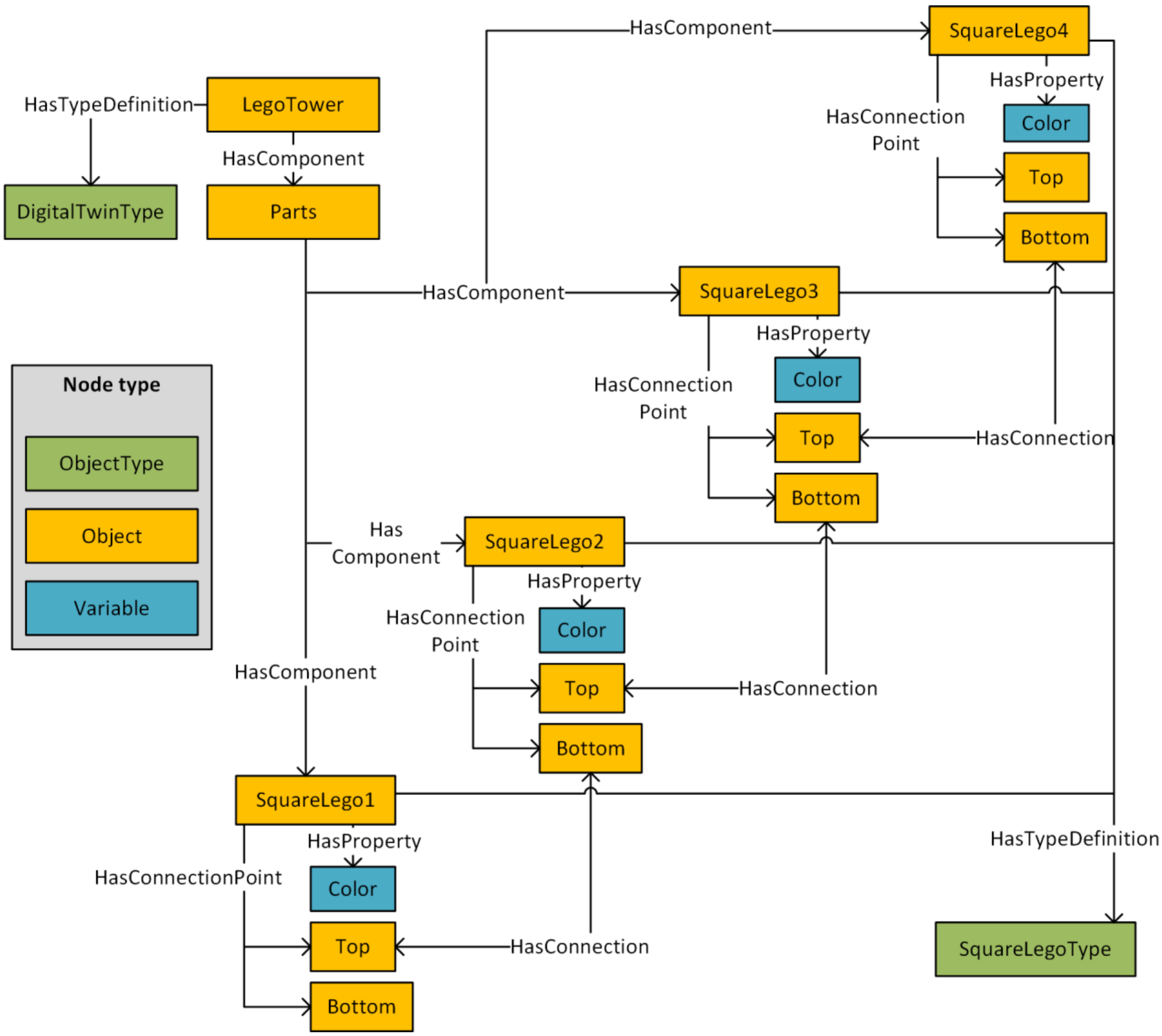

Figure 6 Excerpt of an OPC UA address space related to one digital product description

4 Implementation

4.1 Server side

The OPC UA server side corresponds to the 'OEM' in Figure 1 and Figure 3.

The concept in section 3 was implemented with Prosys OPC UA Java SDK 3.1.2 client-server. First, our custom reference types shown in Figure 4 and our custom object types in Figure 5 are defined in XML according to the XML schema http://opcfoundation.org/UA/2011/03/UANodeSet.xsd defined by OPC Foundation. The following snippet shows the definition for "HasConnectionPoint" in Figure 4.

```
<UAReferenceType NodeId="ns=1;i=97" BrowseName="HasConnectionPoint">
        <DisplayName>HasConnectionPoint</DisplayName>
        <Description>The type for reference from node to its connection point.
        </Description>
        <References>
                <Reference ReferenceType="HasSubtype" IsForward="false">i=47</Reference>
        </References>
        <InverseName>ConnectionPointOf</InverseName>
```

```
</UAReferenceType>
```

The reference is a subtype of the reference with alias 47, which according to the following snippet is “HasComponent”. Accordingly in Figure 4, “HasConnectionPoint” is a subtype of “HasComponent”.

```
<Alias Alias="HasComponent">i=47</Alias>
```

The following snippet is an example of a new object type definition:

```
<UAObjectType NodeId="ns=1;i=10" BrowseName="CadPartType">
        <DisplayName>CadPartType</DisplayName>
        <References>
                <Reference ReferenceType="HasSubtype" IsForward="false">ns=1;i=102</Reference>
                <Reference ReferenceType="HasComponent">ns=1;i=10201</Reference>
                <Reference ReferenceType="HasProperty">ns=1;i=10202</Reference>
                <Reference ReferenceType="HasProperty">ns=1;i=10301</Reference>
                <Reference ReferenceType="HasProperty">ns=1;i=10203</Reference>
                <Reference ReferenceType="HasProperty">ns=1;i=11</Reference>
        </References>
</UAObjectType>
```

This specifies that “CadPartType” is a subtype of the node with node id “ns=1;i=102”. According to Figure 5, “CadPartType” is a subtype of “DigitalPartType”. From the following snippet it can be confirmed that the node id of “DigitalPartType” is indeed “ns=1;i=102”.

```
<UAObjectType NodeId="ns=1;i=102" BrowseName="DigitalPartType">
```

The full XML file containing the definitions is 1400 lines. A code generator included in the Prosys OPC SDK was used to generate Java source code for classes corresponding to our custom defined reference and object types. On the OPC server side Java code, digital product specifications are now created. Below is a snippet for a function createProduct0() which creates a lego tower. A subassembly of the lego tower consists of 4 yellow square legos stacked on top of each other, as in Figure 6. The snippet below includes only the code for creating this subassembly. The comments in the snippet identify 4 steps, which accomplish the following:

1. An object of DigitalTwinType is created corresponding to the yellow “DigitalTwin” box in Figure 5 and the yellow “LegoTower” box in Figure 6. This node as well as a reference to the address space’s top level folder “objectsFolder” is added to the address space. The DigitalTwinType class that was automatically created from the XML is utilized here.
2. For objects of SquareLegoType are created, corresponding to the yellow “SquareLego” boxes in Figure 6. As can be seen in Figure 6, each of these objects has a variable “Color”. The automatically generated Java code has a setter method “setColor()” for this variable, which is used to assign the value of the variable. Finally, the objects are stored in a hashmap for step 3.
3. As can be seen in Figure 6, the “top” connection point of one lego is connected to the “bottom” connection point of the lego above it using our custom defined reference type “HasConnection”. The first two lines of Java code retrieve these connection point objects. The third line creates the reference of type “HasConnection” between the connection points.

```
protected void createProduct0() throws StatusException, ServiceException {
  // step 1
  final NodeId digitalTwinId = new NodeId(namespaceIndex, 20);
```

```
  DigitalTwinType digitalTwin = createInstance(DigitalTwinType.class, "lego.txt", digitalTwinId);
  addNodeAndReference(objectsFolder, digitalTwin, Identifiers.Organizes);

  // step 2
  Map<String, SquareLegoType> squares = new HashMap<String, SquareLegoType>();
  for (int i = 0; i < 4; i++) {
   final NodeId legoSquareId = new NodeId(getNamespaceIndex(), UUID.randomUUID());
   SquareLegoType squareLego = createInstance(SquareLegoType.class, "Square"+(1+i),
legoSquareId);
   squareLego.setColor("yellow");
   addNodeAndReference(digitalTwin.getDigitalPartsNode(), squareLego, Identifiers.HasComponent);
   squares.put("Square" + (1 + i), squareLego);
  }

  for (int i = 1; i < 4; i++) {
   UaNode sourceNode = squares.get("Square" + i).getBottomNode();
   UaNode targetNode = squares.get("Square" + (1 + i)).getTopNode();
   addReference(sourceNode, targetNode, hasConnectionId, false);
  }
}
```

4.2 Client side

The OPC UA client side corresponds to the ‘Manufacturer’ in Figure 1 and Figure 3. In Figure 3, there is a message line from the OEM’s activity ‘Develop and send digital product description’ to the Manufacturer’s ‘Perform virtual assembly’ activity. How this is implemented with OPC UA will be elaborated in this section. It is assumed that the Manufacturer knows the OPC UA node id of the digital twin object (e.g. the yellow box ‘LegoTower’ in the simple product description in Figure 6). When the technology standardization of the Functional layer of RAMI 4.0 (see Figure 2) is more mature, executable business processes at this level could communicate this node id across organizations. In our proof-of-concept, the node id is simply given as input to the client side software. After connecting to the server, the client retrieves the digital twin object using the said id (‘digitalTwinId’ in the following snippet). Then, using the getter methods that were autogenerated from our XML descriptions, all of the parts in the ‘Parts’ folder are retrieved and added to a list. An explicit type casting from ‘UaNode’ to ‘DigitalPartType’ node is then performed; the class definition for ‘DigitalPartType’ was autogenerated from our XML descriptions and corresponds to the green box ‘DigitalPartType’ in Figure 5.

```
List<DigitalPartType> parts = new ArrayList<DigitalPartType>();
DigitalTwinType digitalTwin = (DigitalTwinType) client.getAddressSpace().getNode(digitalTwinId);
UaNode partsNode = digitalTwin.getDigitalPartsNode();
UaNode[] nodes = partsNode.getComponents();
for (UaNode node : nodes) {
       parts.add((DigitalPartType) node);
}
```

Next, for each part, the connection points are obtained. The following snippet assumes that the node id of the reference type ‘hasConnectionPoint’ (see Figure 4 and Figure 5) has been previously obtained from the server and stored in ‘hasConnectionPointId’. The first line in the snippet gets all the references of this type pointing from this part to some other object. The second line creates an array of type ‘CoordinateType’ (this type being autogenerated from the XML specifications corresponding to Figure 5). The number of elements in this array is the number of references that were obtained by the first line of code. The for loop gets the target node of each reference, i.e. a connection point, and stores that in the array.

```
UaReference[] refs = part.getForwardReferences(hasConnectionPointId);
```

```
CoordinateType[] connectionPoints = new CoordinateType[refs.length];
for(int i=0; i<refs.length; i++) {
        connectionPoints[i] = (CoordinateType) refs[i].getTargetNode();
}
```

Next, the connection points are examined in order to find the connections between point. The node id of the reference type ‘hasConnection’ (see Figure 4) has been previously obtained from the server and stored in ‘hasConnectionId’. Figure 6 shows some examples of this this type of reference is used to link connection points of two parts. The snippet below loops through all of the connection points obtained from the previous snippet and looks for references of type ‘hasConnection’. The methodology in [30] does not specify any direction to the connections, but OPC UA requires that all references have a direction, thus the loop looks for forward as well as inverse references.

```
Set<UaReference> connections = new HashSet<UaReference>();
for(CoordinateType connectionPoint : connectionPoints) {
        UaReference forwardConnection = connectionPoint.getReference(hasConnectionId, false);
        if(forwardConnection != null) {
                connections.add(forwardConnection);
        }
        UaReference inverseConnection = connectionPoint.getReference(hasConnectionId, true);
        if(inverseConnection != null) {
                connections.add(inverseConnection);
        }
}
```

Naturally, these snippets are a very minor part of the code. Based on these examples, a computer science expert who consults the documentation of the OPC UA SDK should be able to develop applications that exchange digital product descriptions across organizational boundaries, either according to the address space proposed in section 3 or some other user defined address space. The server side and client side software is deployed in different applications that may be run on the local host for testing purposes or on different machines anywhere in the Internet as long as the firewall settings allow the client to connect to the server. Once the digital product description data is exchanged, the system developed in [30] is used to perform the virtual and physical assembly and to complete the proof-of-concept.

5 Results

First, the server side application is run. After the server is running, before starting the client, it is possible to browse the server address space with a visual third party tool to ensure that the expected information is present. This is also a good way to check that the implementation indeed conforms to the OPC UA standard and is accessible to any client side application, not only the one that was developed by the authors. The free UaExpert tool was used for this purpose. The tool is available from:

https://www.unified-automation.com/products/development-tools/uaexpert.html

Figure 7 shows a screenshot from UaExpert after the server has been connected. In the ‘Address Space’ pane on the left, one can see the ‘Objects’ folder, which is the top level folder of the server’s address space. In the folder, that are two object of type ‘DigitalTwin’: ‘lego tower’ and ‘cranfield’. The former is a more complex version of the example in Figure 6. The latter is the Cranfield assembly benchmark [114] consisting of 6 different types of CAD components. The ‘Parts’ folder of ‘lego tower’ is open. In it, the details of the part ‘Square1’ are open. The ‘Color’ variable has been dragged to the ‘Data Access View’ pane, in which the value pink can be read and modified.

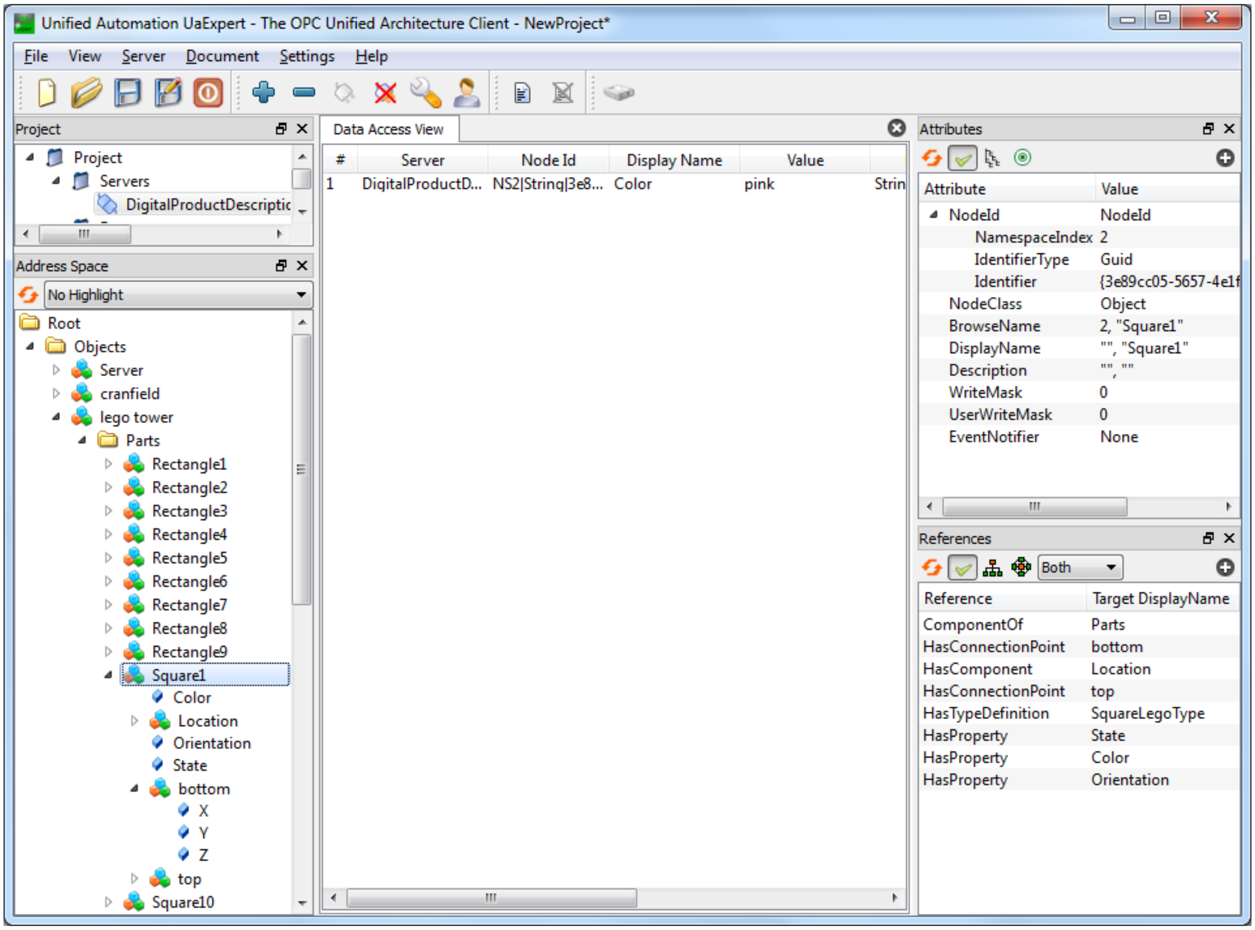

Figure 7 Browsing the server with UaExpert

Figure 8 shows a sequence of screenshots from the virtual assembly of the Cranfield assembly benchmark, clockwise starting from top left. On the top left, an assembly station with the parts and a Cartesian robot with an additional two rotting joints is ready to begin the virtual assembly. The remaining screenshots show how, based solely on the digital product description information from the OPC UA server, the method from [30] is able to perform the assembly with correct assembly sequence planning. One concrete example of this is that the green shaft is inserted to the center of the faceplate before the yellow pendulum (top right). Another example is that all the green bolts are inserted before the top faceplace is put into place (bottom right).

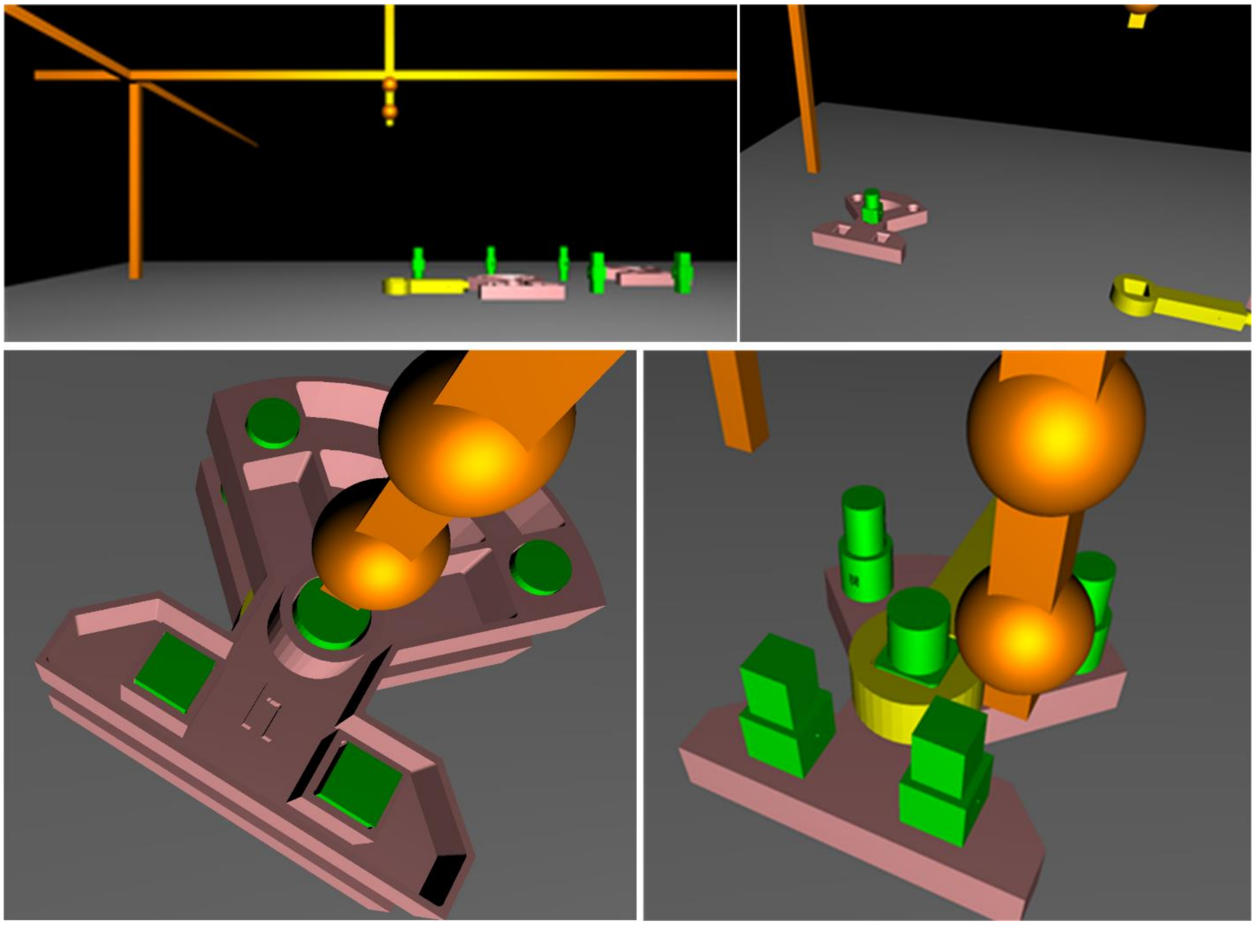

Figure 8 Sequence of screenshots from the virtual assembly of the Cranfield benchmark: clockwise starting from top-left

6 Conclusion

6.1 Research goal 1

Regarding RG1, the literature review in section 2 revealed a worrisome disconnection between the industry-led technology standardization and the main bulk of academic research on Industry 4.0. In particular, the great majority of authors proposing new Industry 4.0 architectures did not demonstrate awareness of RAMI 4.0 or IIRA or any other industrially recognized architecture such as IMSA or IVRA. Certainly, academics are not required to base their work on architectures originating from the industry, but it is unfortunate that these research works lacked a discussion about any compatibility issues of their proposal with the industrially accepted architectures and about the implications of any such issues on the eventual industrial impact of the research. This is especially problematic due to the fact that the only Industry 4.0 architectures that have been taken up by major international standardization organizations are RAMI 4.0 and IIRA, which are being standardized by the IEC and OMG, respectively. Further, the academic community seems to use the terms IIoT and CPPS interchangeably, evinced by the similarity of the literature reviews for IIoT and CPPS in section 2. The IIC's IIoT reference architecture IIRA is ignored by the academic community and individual researchers frequently do not explain their choice of term between IIoT and CPPS. Numerous individual researchers have proposed their own IIoT or CPPS architectures, but there is a lack of any coordinated effort by a large number of groups from several countries.

Research goal 2

The findings with respect to RG2 will be assessed by considering the layers of RAMI 4.0 (see Figure 2) starting from the bottom. The lowest 2 layers were not specifically addressed in this simulation based work. In any further research in a physical environment with equipment and systems from different vendors, the OPC UA would need to be complemented with hardware and software components that support the Industry 4.0 Component Model [49]. As noted in section 2.5, the Component Model is still at an early stage and there is no standard ready to support technology implementation. For the communication layer, a straightforward application of OPC UA was performed; the technology for this layer of RAMI 4.0 was found to be mature. In the "Information" layer the content of the information to be exchanged is defined in a machine readable and non-proprietary way. The literature review in section 2 revealed that a large number of researchers in IIoT and CPPS are applying ontologies for this purpose. In RAMI 4.0, OPC UA address spaces are defined using XML, as illustrated in section 4.1, instead of ontology technology such as OWL [49]. It would be very desirable that other researchers and practitioners would publish detailed proposals on OPC UA address spaces for digital product descriptions. This would build the critical mass for defining an OPC UA companion specification to ensure consistent modeling across organizational boundaries. Finally, the top two layers of RAMI 4.0 were not included in the implementation, since no technology standardization is yet underway. Thus, only a non-executable BPMN business process was proposed in Figure 3; a similar approach was taken in [78].

6.3 Outlook

The developments related to the top two layers of RAMI 4.0 will significantly influence the true extent of the Fourth Industrial Revolution beyond the current progress with OPC UA. Numerous publications cited in this article anticipate a radical flattening or dissolution of the automation pyramid architecture, which would indeed be the case if RAMI 4.0 were fully implemented. However, there is a lack of research addressing the role of ERP and MES systems in an era that would follow a complete dismantling of the automation pyramid. It is interesting to note that the dominant German ERP vendor SAP has taken a leading role in competing efforts at the Industrial Internet Consortium [115], which may be a part of the reason behind the slow progress in the RAMI 4.0 upper layers. One possible architecture that could emerge would be a hybrid consisting of the lowest four layers of RAMI 4.0 and the top of the automation pyramid consisting of the ERP and possibly also the MES. Such a future is not being predicted by the majority of the literature reviewed in this paper, but neither did the majority of the research offer insights to the future role of the dominant MES and ERP players in a CPPS, IIoT or RAMI 4.0 architecture. Thus, the minority of researchers in EA and EI reviewed in section 2.3 may yet prove to be correct in their unwillingness to predict revolutionary developments to the top part of the automation pyramid.

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