Siivonen, J., Naakka, K., Salminen, K., Kärki, T. & Aho, M. (2023) Industrial Data Pipelines for Manufacturing Applications. Procedia CIRP, 2024, s. 69-74.

URL: https://doi.org/10.1016/j.procir.2023.08.013

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 120 (2023) 69–74

www.elsevier.com/locate/procedia

56th CIRP Conference on Manufacturing Systems, CIRP CMS ‘23, South Africa

Industrial Data Pipelines for Manufacturing Applications

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Abstract

Small and medium enterprises (SMEs) struggle with the uptake of industrial data in their business. SMEs have expressed interests to integrate physical legacy machines in factories and uptake Industrial Internet of Things (IIoT) for data-driven industrial processes. A widely recognizable aids for companies are testbeds or test-before-invest environments where companies can familiarize themselves with Industry 4.0 (I4.0) technologies. In this paper, an easily scalable approach to collect industrial data is presented. The environment can be used by SMEs to benchmark the developed solutions using affordable licenses and test aspects of the industrial data best suitable for their purposes before making investments. In TAMK FieldLab I4.0 pilot trial, horizontal integration is done in between I4.0 field and control layer to integrate different machines’ data to common database and common format to be used for visualization and later for data analysis. The focus of the paper is on data connectivity capabilities. The trial utilize data from different machines. First phase includes exporting data from different machines to same data table with time stamps, to enable comparison of data with same time base. With common time base it’s possible to produce synchronized timeseries data visualization from all TAMK FieldLab’s machines. Used common database is PostgreSQL, where data from all machines is stored. For horizontal field level integration minimum amount APIs and protocols is used. For common API protocol MQTT was chosen as it’s lightweight and supported widely. ABB robot data is taken trough OPC/UA and MQTT. From Omron mobile robot data is transferred trough ARCL. The paper will identify gap areas of the implementation in comparison with I4.0 and when appropriate, RAM 4.0 framework. Finally, the next steps that will be taken in near future regarding artificial intelligence (AI) and upgrading the IIoT system to match with RAMI 4.0 framework will be presented.

Keywords: Industrial Internet of Things; RAMI 4.0; Industry 4.0

1. Introduction

The on-going Fourth Industrial Revolution (IR4) is fostering digitalization in all industry sectors. Cyber Physical Systems (CPS) combine physical world with digital control systems enabling bi-directional feedback loops [1]. Data exchange is a key feature of the CPS [2], making it elementary to have a proper access for reading and manipulating the required data. In manufacturing industry this data is typically related to manufacturing equipment and processes [3]. The data from manufacturing processes is heterogenous as it can be collected from manufacturing information systems, equipment, smart products and even from users.

Generally, Small and Medium Enterprises (SMEs) are lagging behind larger companies in digital transformation [4] up to the point where the digital maturity of the SMEs can be too low to be addressed using standard I4.0 maturity models [5]. Due to the SMEs’ remarkable role in building financial and

10.1016/j.procir.2023.08.013

social welfare in society, it is essential to support their growth and proceeding on digitalization pathway. Previous studies clearly show that data can build a competitive edge for companies [6].

Typically, SMEs have their digital data spread across several separate IT-systems, making it hard and time consuming to utilize. Nagorny et al. (2020) have identified three main categories for reasons that make the selection and extraction of data so time consuming activity; Data chaos, Inefficient data understanding and selection and Time and resource consuming data extraction [7]. To support the SME's development activities and investment decision making around the topic, open reference setups for benchmark are needed.

This paper introduces an approach for building a lightweight, scalable, and affordable data acquisition testbed setup in the manufacturing industry context. The paper addresses the following research questions:

1. What elements and sub-systems are needed to build a lightweight and scalable data acquisition testbed setup for manufacturing industry, with multi-brand manufacturing equipment?
2. How does the developed architecture correspond to Reference Architecture Model Industrie 4.0 (RAMI 4.0) framework model?

To address these research questions, a case-study research work was conducted at the Tampere University of Applied Sciences (TAMK) FieldLab which is an Industry 4.0 testbed environment. Based on the technology review and previous studies [8] a set of subsystems, architectures and protocols were selected for building a pilot data pipeline. After implementing the system for selected manufacturing equipment, the performance of the data transfer was tested, and the results were compared to industrial requirements. Also, the pilot setup was analyzed to compare the solution with the RAMI 4.0 architecture.

The paper is constructed as follows: Chapter two outlines theoretical background by introducing some key technologies and protocols for building the data acquisition elements of the data pipeline in industrial context. RAMI 4.0 framework is also briefly explained. Chapter three focuses on the research results and introduces the proposed solution. Testbed correspondence with the RAMI 4.0 framework model is analyzed there as well, and implementation environment TAMK FieldLab is described shortly. The paper is concluded with chapter four focused on discussing the results and addressing future research topics.

2. Industry 4.0 Testbeds, protocols and technologies used in current studies

Universities and research institutes are currently implementing testbeds and pilot lines for the use of the industry. In practice, this means testing facilities that will enable SMEs to familiarize themselves with emerging manufacturing technologies before investing to them. The usability of testbeds in prototyping small patch sizes, prototyping [9] adaptation of new technologies in a reconfigurable pilot set up [10], technology scale-up [11] piloting manufacturing processes such as binder jetting [12] or product life-cycle management [13].

2.1. RAMI 4.0 and related technologies

Reference Architecture Model Industrie 4.0 (RAMI 4.0) was introduced in 2015 to describe the interrelations of Industry 4.0 elements and to streamline their implementation and communication around the topic [14]. Standard DIN SPEC 91345:2016-04 defines the model in detail. The core of the model is presented in three-dimensional illustration as shown in Figure 1.

The vertical layers of RAMI 4.0 describe the ICT perspective of representing the I4.0 [15]. First horizontal axis expresses the product life-cycle states and the second shows the hierarchy levels representing functional hierarchy of connected objects based on IEC 62264, supplemented with levels "Connected World", "Field Device" and "Product" [16].

Even though RAMI 4.0 can be seen as an tool for integrating different standards of automation [17] and a way to model wide smart supply chains [18], adoption of the model is typically only partial or otherwise limited [16]. Kirmse et al. (2019) propose an agent-based information architecture model, covering six out of seven RAMI 4.0 layers. The lowest level, Asset, is excluded thus the model is focused on digital world, not on physical entities [19]. Schulte and Colombo (2017) represent a migration process for upgrading a legacy industrial manufacturing device into a RAMI 4.0 compliant digitalized system. In their research validation showed positive outcomes, but further work was recognized around topics of interoperability and connectivity [20]. When evaluating architecture compliance with RAMI 4.0 model, the mapping of proposed sub-solutions and functionalities to RAMI dimensions is important. Flatt et al. (2016) use visual illustration to represent the mapping of functionality and data of their use case in RAMI 4.0 framework [21]. Visual representation of multi-dimensional system architecture is complex, but when realized successfully, it gives valuable insight about the system structure.

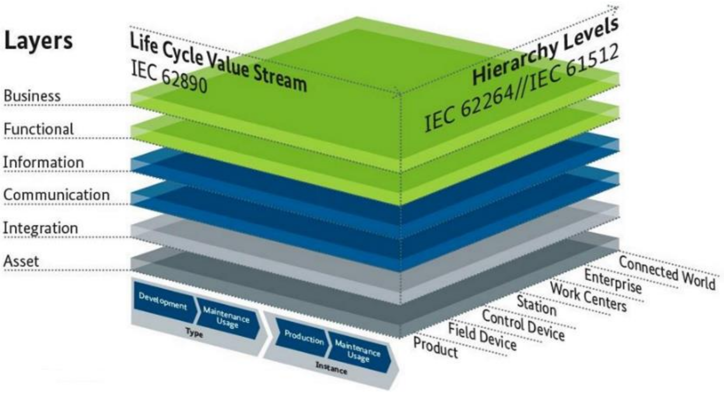

Figure 1: RAMI 4.0 framework. [14]

Vertical and horizontal data flows are in the core of the Industry 4.0 concept. This requires standardized interfaces. Asset Administration Shell (AAS) is a digital representation of an Industry 4.0 asset, ensuring the interoperability between applications [22]. Figure 2, adopted from [23], illustrates the AAS and its content. Several applications and case studies related to AAS can be found in resent papers [24-27]

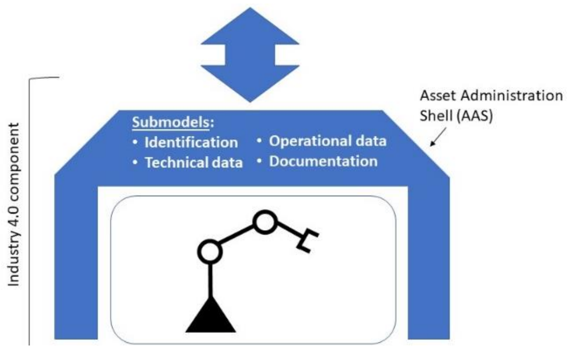

Figure 2. Asset Administration Shell. (Adapted from [23])

Several technologies and protocols are available for implementing the data processes in RAMI 4.0 context. Currently, the most important protocol for Industrial Internet of Things (IIoT) applications and thus for RAMI 4.0 is OPC UA (OLE for Process Control Unified Architecture). It has achieved a status of *de facto standard* for IIoT communication protocol. It offers both “Client-Server” method as well as “Publish-Subscribe” method to execute the communication. OPC UA is also recommended by the German Industry 4.0 agency. [28]

Message Queuing Telemetry Transport (MQTT) is a broker -based publish/subscribe (pub/sub) protocol for lightweight communication [29]. Its lightweight character makes it especially suitable for conditions and devices with limited resources like bandwidth or memory. Broker holds the data on behalf of the devices, releasing their limited resources [30].

Representational State Transfer (REST) is an architecture based on “Client-Server” method, and includes caching for storing frequently accessed data [31]. It uses HTTP protocol and is widely supported by web frameworks.

3. Developed testbed solution utilizing RAMI 4.0 framework

Tampere University of Applied Sciences has systematically developed its Industry 4.0 research, development and learning environment. Manufacturing devices in this laboratory, titled TAMK FieldLab, formed the asset layer for the case study setup. It includes mobile robots, machining centers and industrial robots, both traditional robots and collaborative robots. Architecture overview to the TAMK FieldLab Industry 4.0 Testbed setup is presented in figure 3. Besides the manufacturing assets considered as “Stations” and “Work Centers” in RAMI 4.0 model, some standalone sensors were

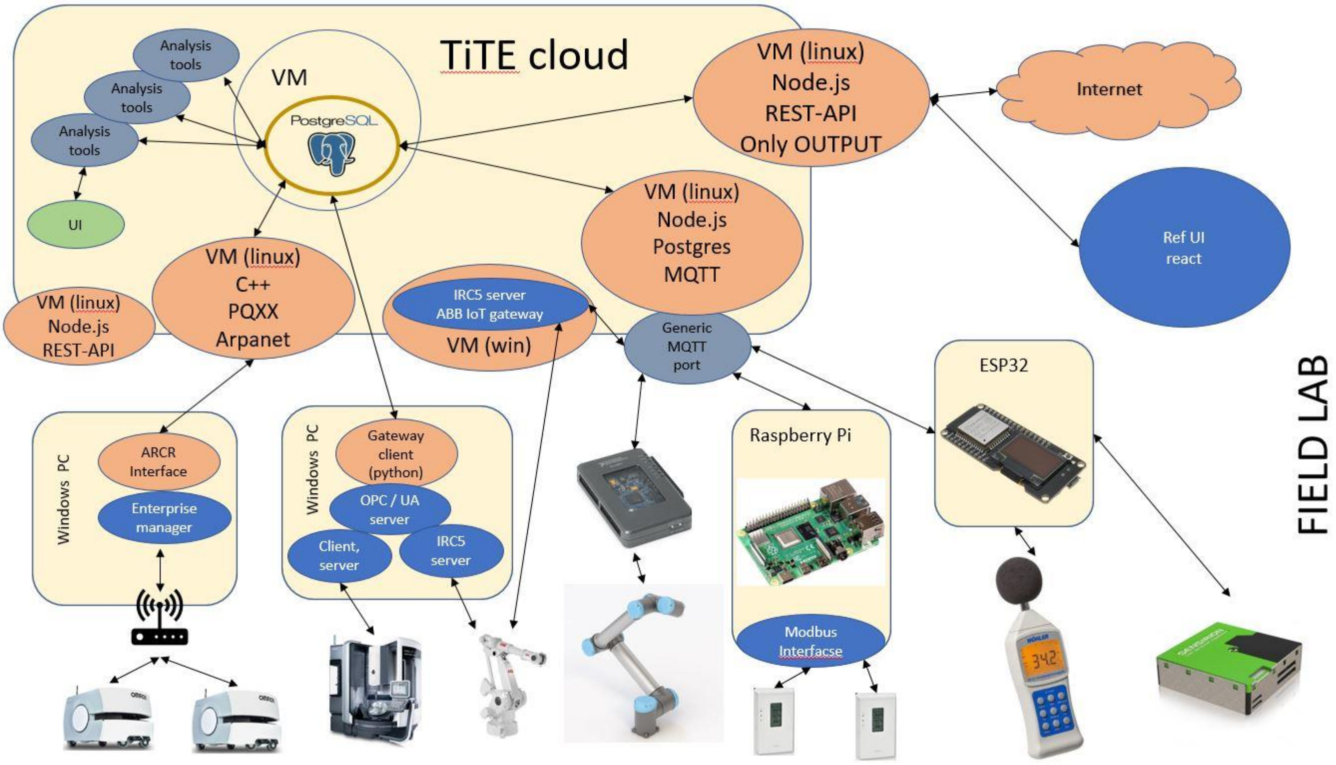

Figure 3: TAMK FieldLab Industry 4.0 Testbed architecture

also included in the setup. These correspond to “Field Devices” of the RAMI 4.0 model.

Some manufacturing assets of the setup are brand new with modern data interfaces like OPC UA or REST. Older legacy devices have very limited connectivity properties. The range in device ages and variety of available interfaces makes the setup similar to the typical situation in SME manufacturing enterprises.

Several methods are used to transform the device-specific data from physical assets into common database. These include microcontroller and minicomputers (ESP32, Rasperry Pi 4), portable reconfigurable I/O boards (National Instruments MyRIO) as well as standard Windows PCs. OPC UA and MQTT are the main protocols used to transfer the data to the common database. The common database is built on PostgreSQL utilizing a custom-made FieldLab data model. The database is running on a virtual machine on a cloud service hosted by the university. Customized gateway software is required to fit machine proprietary API (ARCL) with database API. Gateway is responsible for data polling from machine API and fitting the data for FieldLab data model. Both Windows and Linux virtual machines are used to run the gateway software.

Rest-API is used for taking data out from database to reference UI and for analyzing tools/applications. Currently main application for data utilization is reference user interface (UI) for data visualization, build with JavaScript React library. Several analysis tools are under development, e.g. for energy consumption monitoring and optimization.

Figure 4 illustrates how applied technologies and protocols are mapped to RAMI 4.0 hierarchy levels and layers. To ensure readability of the image, only few assets and their related data pipelines are presented.

Several small-scale pilots were established to verify the functionality of the developed solution. These indicate that the interfaces described in Figure 3 are functional and the proposed data pipelines can be utilized for data collection. Omron LD90 mobile robot’s location data was collected through Omron’s ARCL interface and imported to the PostgreSQL database through the customized gateway. Location data was then visualized with reference user interface. ABB industrial robot (IRB 4600) was connected to PC running an ABB proprietary gateway software (ABB IoT Gateway) which delivered MQTT messages to a broker software for importing the data to PostgreSQL database.

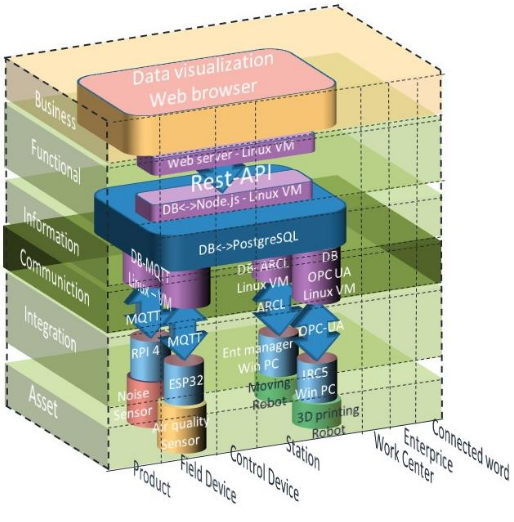

Figure 4: Testbed mapping to RAMI 4.0 framework

To validate the solution’s suitability for future system performance tests, a simple MQTT trigger test was executed for the ABB IRB 4600 robot. Five time-based triggers (A-E) with different trigger intervals were logged, as well as one software variable based trigger (R). Data in table 1 indicates that variable based trigger is more unreliable in this setup and that differences in performance can be detected from the data generated from developed system.

Table 1. Initial MQTT trigger performance tests. (Modified from [32])

Trigger	Trigger interval	Number of messages	Number of missed messages	Percentage of missed messages
A	00:00,110	19123	90	0.47%
B	00:00,100	21035	87	0.41%
C	00:00,120	17529	84	0.48%
D	00:00,130	16181	88	0.54%
E	00:00,140	15025	81	0.54%
R	00:00,320	6573	243	3.75%

4. Conclusions

This paper presents one relevant approach for building a lightweight and affordable testbed setup for Industry 4.0 data acquisition. The data pipeline is presented from the asset level up to business layer of RAMI 4.0 model [14]. The machinery fleet is well suited for the case study, since it has similar characteristics as typical manufacturing SMEs such as machines with different ages and from several vendors with different connectivity capabilities and protocols. The case study proves that selected technologies and protocols are applicable when building a testbed setup for Industry 4.0 data pipeline. Correspondence between the testbed architecture and RAMI 4.0 model is also described and visualized.

Even though the approach as such can be considered successful, some limitations can be identified. Mostly due to pursuit for affordability and scalability, the setup ended having several tailored software components. While addressing objectives important for future research work (like setup flexibility), it simultaneously expands the expertise required for maintaining and configuring the setup. This limits the potential to utilize the overall setup as a direct reference for industrial applications see, for example, [33] for a method to use RAMI4.0 in a factory.

Asset Administration Shell (AAS) concept is only evolving in the setup and currently AASs are not implemented. Several tailored gateway software have some similar properties as AAS, but e.g. data model is not coherent. More research is needed to apply the AAS concept to the testbed.

Some performance tests were executed for the developed solution. They show that system can be utilized for evaluation of different data pipeline protocols and settings. Important future research topic is performance evaluation of the testbed setup see, e.g. [34] for a setup for performance evaluation in I4.0 context. In current research, only very limited latency tests were executed, and results are only indicative. More comprehensive analysis about the quality, reliability and latency of the data transmission is required.

To address the forementioned deficiencies and to improve the testbed performance several future research topics are identified. Comprehensive performance tests will be carried out and reported, including comparison between data transport protocols. The testbed will also be expanded with some publicly available Fiware components. This enables comparison of different subsystem level solutions, supports data model development and AAS concept implementation as well as reduces the number of tailored software components.

Acknowledgements of organizations that funded the research

Sustainable Industry Ecosystem, Academy of Finland. Decision number: 337722.

Building a Competitive Edge in a Fair Data Economy for Higher Education (FairDatAct), Ministry of Education and Culture in Finland. Decision number: OKM/18/524/2022.

References

[1] E. Lee, The Past, Present and Future of Cyber-Physical Systems: A Focus on Models, Sensors. 15 (2015) 4837–4869.

[2] N. Jazdi, Cyber physical systems in the context of Industry 4.0, in: 2014 IEEE International Conference on Automation, Quality and Testing, Robotics, 2014: pp. 1–4.

[3] F. Tao, Q. Qi, A. Liu, A. Kusiak, Data-driven smart manufacturing, Journal of Manufacturing Systems. 48 (2018) 157–169.

[4] B. Marco, SME Digitalisation to “Build Back Better,” (2021).

[5] S. Mittal, M.A. Khan, D. Romero, T. Wuest, A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs), Journal of Manufacturing Systems. 49 (2018) 194–214.

[6] H. Ahuett-Garza, T. Kurfess, A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart manufacturing, Manufacturing Letters. 15 (2018) 60–63.

[7] K. Nagorny, S. Scholze, A.W. Colombo, J.B. Oliveira, A DIN Spec 91345 RAMI 4.0 Compliant Data Pipelining Model: An Approach to Support Data Understanding and Data Acquisition in Smart Manufacturing Environments, IEEE Access. 8 (2020) 223114–223129.

[8] K. Zhou, T. Liu, L. Zhou, Industry 4.0: Towards future industrial opportunities and challenges, in: 2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), 2015: pp. 2147–2152.

[9] D.-Y. Kim, J.-W. Park, S. Baek, K.-B. Park, H.-R. Kim, J.-I. Park, H.-S. Kim, B.-B. Kim, H.-Y. Oh, K. Namgung, W. Baek, A modular factory testbed for the rapid reconfiguration of manufacturing systems, J Intell Manuf. 31 (2020) 661–680.

[10] J. Siivonen, S. Pöysäri, A.-M. Hakamäki, M. Lanz, K. Salminen, M. Ijas, M. Aho, H. Nieminen, Reconfigurable Pilot Lines Enabling Industry Digitalization: An Approach for Transforming Industry and Academia Needs to Requirements Specifications, Procedia CIRP. 107 (2022) 1226–1231.

[11] M. Keppeler, H.-Y. Tran, W. Braunwarth, The Role of Pilot Lines in Bridging the Gap Between Fundamental Research and Industrial Production for Lithium-Ion Battery Cells Relevant to Sustainable Electromobility: A Review, Energy Technology. 9 (2021) 2100132.

[12] D. Oropeza, A.J. Hart, A laboratory-scale binder jet additive manufacturing testbed for process exploration and material development, Int J Adv Manuf Technol. 114 (2021) 3459–3473.

[13] M. Helu, T. Hedberg, Enabling Smart Manufacturing Research and Development using a Product Lifecycle Test Bed, Procedia Manufacturing. 1 (2015) 86–97.

[14] G. Koschnick, M. Hankel, Industrie 4.0: The Reference Architectural Model Industrie 4.0 (RAMI 4.0), (2015).

[15] M.A. Pisching, M.A.O. Pessoa, F. Junqueira, D.J. dos Santos Filho, P.E. Miyagi, An architecture based on RAMI 4.0 to discover equipment to process operations required by products, Computers & Industrial Engineering. 125 (2018) 574–591.

[16] J. Contreras, J. Melo, J. Díaz Pastrana, Developing of Industry 4.0 Applications, International Journal of Online Engineering (IJOE). 13 (2017) 30.

[17] M. Resman, M. Pipan, M. Simic, N. Herakovic, A new architecture model for smart manufacturing: A performance analysis and comparison with the RAMI 4.0 reference model, Adv Produc Engineer Manag. 14 (2019) 153–165.

[18] A. Corradi, L. Foschini, C. Giannelli, R. Lazzarini, C. Stefanelli, M. Tortonesi, G. Virgilli, Smart Appliances and RAMI 4.0: Management and Servitization of Ice Cream Machines, IEEE Transactions on Industrial Informatics. 15 (2019) 1007–1016.

[19] A. Kirmse, V. Kraus, T. Langer, A. Pomp, T. Meisen, How To RAMI 4.0: Towards An Agent-based Information Management Architecture, in: 2019 International Conference on High Performance Computing & Simulation (HPCS), 2019: pp. 961–968.

[20] D. Schulte, A.W. Colombo, RAMI 4.0 based digitalization of an industrial plate extruder system: Technical and infrastructural challenges, in: IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, 2017: pp. 3506–3511.

[21] H. Flatt, S. Schriegel, J. Jasperneite, H. Trsek, H. Adamczyk, Analysis of the Cyber-Security of industry 4.0 technologies based on RAMI 4.0 and identification of requirements, in: 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA), 2016: pp. 1–4.

[22] Federal Ministry for Economic Affairs and Climate Action (BMWK), Details of the Asset Administration Shell Part1 V3.pdf, (n.d.).

[23] Plattform Industrie 4.0, The Asset Administration Shell: Implementing digital twins for use in Industrie 4.0, (n.d.).

[24] X. Ye, S.H. Hong, W.S. Song, Y.C. Kim, X. Zhang, An Industry 4.0 Asset Administration Shell-Enabled Digital Solution for Robot-Based Manufacturing Systems, IEEE Access. 9 (2021) 154448–154459.

[25] P. Marcon, C. Diedrich, F. Zezulka, T. Schröder, A. Belyaev, J. Arm, T. Benesl, Z. Bradac, I. Vesely, The Asset Administration Shell of Operator in the Platform of Industry 4.0, in: 2018 18th International Conference on Mechatronics - Mechatronika (ME), 2018: pp. 1–5.

[26] M.A. Iñigo, A. Porto, B. Kremer, A. Perez, F. Larrinaga, J. Cuenca, Towards an Asset Administration Shell scenario: a use case for interoperability and standardization in Industry 4.0, in: NOMS 2020 - 2020 IEEE/IFIP Network Operations and Management Symposium, 2020: pp. 1–6.

[27] S. Cavalieri, M.G. Salafia, Asset Administration Shell for PLC Representation Based on IEC 61131–3, IEEE Access. 8 (2020) 142606–142621.

[28] P. Drahoš, E. Kučera, O. Haffner, I. Klimo, Trends in industrial communication and OPC UA, in: 2018 Cybernetics & Informatics (K&I), 2018: pp. 1–5.

[29] Eurotech, International Business Machines Corporation (IBM), MQTT V3.1 Protocol Specification, (n.d.).

[30] S. Profanter, A. Tekat, K. Dorofeev, M. Rickert, A. Knoll, OPC UA versus ROS, DDS, and MQTT: Performance Evaluation of Industry 4.0 Protocols, in: 2019 IEEE International Conference on Industrial Technology (ICIT), 2019: pp. 955–962.

[31] R. Schiekofer, A. Scholz, M. Weyrich, REST based OPC UA for the IIoT, in: 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), 2018: pp. 274–281.

[32] T. Kärki, Tuotantoympäristön Industry 4.0 -tie- toliikennejärjestelmän kehittäminen, 2022.

[33] A. Bastos, M.L. Sguario Coelho De Andrade, R.T. Yoshino, M.M.D. Santos, Industry 4.0 Readiness Assessment Method Based on RAMI 4.0 Standards, IEEE Access. 9 (2021) 119778–119799.

[34] J. Wan, S. Tang, Z. Shu, D. Li, S. Wang, M. Imran, A.V. Vasilakos, Software-Defined Industrial Internet of Things in the Context of Industry 4.0, IEEE Sensors Journal. 16 (2016) 7373–7380.