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Software infrastructure for ready-to-use, data analytics-based Digital Twins utilising the Asset Administration Shell

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Abstract

The advance of the Industrial Internet of Things has largely increased the availability of shop floor data for software applications in production management. Digital Twins utilise shop floor data to provide synchronised virtual representations of production resources, e.g. by applying Data analytics such as Machine Learning techniques. A main barrier to take advantage of the potential of Digital Twins is the personnel effort and skills required for development, which can be lowered by ready-to-use approaches. This article proposes a corresponding software infrastructure. Prebuilt and configurable Digital Twin components are allocated to suitable platforms and linked by suitable data connections. To enable interoperability with production management applications, the standard of the Asset Administration Shell is utilised. Establishing resource-specific shop floor data connection and transformation is facilitated by a shopfloor integration platform, which provides configurable components. The software infrastructure is demonstrated in a laboratory environment, where Digital Twins of a manufacturing machine and an assembly robot entail Machine Learning models to predict and provide capacity parameters to a discrete event simulation.

Keywords: production management; data analytics; Digital Twin; Asset Administration Shell; interoperability

1. Introduction

Due to the advances of IIoT, shop floor data is widely available for production management applications [1]. Shop floor data is a key element of Digital Twins, which offer detailed and accurate virtual representations of production

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resources. Digital Twins utilise data connections to the shop floor to synchronise information and models that assist simulation, optimisation, and decision-making [2, 3]. In production management, they support tasks such as capacity planning, maintenance planning, and quality assurance. Data analytics is applied for descriptive and predictive models, e.g. supervised Machine Learning to map correlations between influencing factors and predicted parameters [3].

A barrier to deploying Digital Twins is the high effort and difficulty of development [4], which ready-to-use approaches aim to minimise [5]. They utilise prebuilt, generic, and configurable components, where interoperability standards enable immediate data connections.

The AAS is an interoperability standard for Digital Twins in compliance with DIN's specification 91345 [6]. The specification defines how industrial assets, such as production resources, are virtually represented in line with Industry 4.0 concepts. The AAS provides a singular data access point for software applications. It contains information and knowledge to represent a production resource, while integrating lower-level shop floor data for modelling.

This article proposes a software infrastructure for the envisioned ready-to-use Digital Twins based on the AAS, which existing approaches have not yet comprehensively described. Prebuilt and configurable data and algorithm components required for data analytics are allocated to suitable platforms and network layers, linked by suitable data connections. First, Section 2 presents related studies, and Section 3 illustrates the context of the article based on existing reference models. Section 4 then conceptualises the proposed software infrastructure, which is demonstrated in Section 5. Subsequently, the findings are discussed in Section 6, and an outlook is given in Section 7.

Nomenclature

5G	5th generation cellular network
AAS	Asset Administration Shell
API	Application Programming Interface
BaSyx	Basic Administration Shell development framework
CoAP	Constrained Application Protocol
CRISP-DM	Cross-Industry Standard Process for Data Mining
DIN	German Institute for Standardisation
FTP	File Transfer Protocol
HTTP	Hypertext Transfer Protocol
IDTA	Industrial Digital Twin Association
IEC	International Electrotechnical Commission
IIC	Industry IoT Consortium
IIoT	Industrial Internet of Things
IP	Internet Protocol
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation for Linked Data
LAN	Local Area Network
MQTT	Message Queuing Telemetry Transport
MTConnect	Manufacturing Technology Connectivity
OPC UA	Open Platform Communications Unified Architecture
RAMI 4.0	Reference Architecture Model Industry 4.0
REST	Representational State Transfer
SOA	Service-oriented architecture
SOAP	Simple Object Access Protocol
SQL	Structured Query Language
TCP	Transmission Control Protocol
TSN	Time-Sensitive Networking
UDP	User Datagram Protocol
XML	eXtensible Markup Language

2. Related studies

With the emergence of Digital Twins in production, software infrastructures have been described that utilise data connections to shop floor data for data analytics, as for example by [7] and [8]. Subsequently, semantics were seen as an important element for the interoperable communication with software applications. [9] as well as [10] deploy JSON-LD to represent Digital Twins of production resources, a data format that allows to amend context information. However, as merely a data format, JSON-LD does not provide standardised data models that map domain knowledge for the uniform representation of production resources. It also does not define an underlying connectivity framework that enables technical interoperability.

Interoperability standards that – on top of uniform connectivity frameworks – incorporate unified data models to represent production resources, are highlighted as a necessary enabler for Digital Twins by [11]. Interoperability standards are a central element for the concept of prebuilt, ready-to-use Digital Twins and their underlying software infrastructure [5]. Consortia like ISO, IEC, IIC, OPC Foundation, DIN, and IDTA created specifications in an attempt to establish standards for data connections and data models of Digital Twins of production resources [12].

The infrastructure of OPC UA, the widely adopted interoperability standard for shop floor data acquisition [13], is used by [14] for a Digital Twin of production resources based on data analytics. At the same time, the AAS received significant attention in scientific studies. [15–17] present effective software infrastructures for Digital Twins based on the AAS, but do not consider data analytics. While [18] and [19] mention the integration of data analytics for Digital Twins based on the AAS, they do not detail the software infrastructure to the level of required data and algorithm components, and do not demonstrate the suitability for data analytics.

[20] documents the integration of data analytics into the AAS. However, the suggested infrastructure does not consider design principles to achieve ready-to-use Digital Twins. Specifically, it does not describe a connector and a data transformation component for data preparation – often referred to as Extract, Transform, Load – which is resource-specific and requires significant personnel effort.

The examined studies lack a comprehensive conceptualisation of a software infrastructure for data analytics-based Digital Twins. They do not assess the suitability of the infrastructure provided by different interoperability standards. Existing approaches do not yet address the requirement for reduced development effort, particularly concerning the resource-specific data preparation. These aspects are the objective this article.

3. Reference models

3.1. Ready-to-use, data analytics-based Digital Twin

[5] outline a ready-to-use Digital Twin of production resources – such as manufacturing machines and assembly stations – which includes data analytics components. Semi-static descriptive and predictive models adapt behavioural properties, such as the throughput rate depending on characteristics of the produced products. The models can be of descriptive nature, e.g. statistical indicators and visualisations, or of predictive nature, e.g. regression functions [3]. Following the CRISP-DM methodology, the configurable, resource-specific components of the Digital Twin are a connector to the shop floor to integrate and format data, and a data transformation algorithm to clean and construct data. The prebuilt, generic components are a structured storage for shop floor records, a data analytics algorithm for modelling, and a structured storage for models. In addition, dynamic condition information, e.g. the current work status, and static characteristics, e.g. lot sizes, are provided by the Digital Twin as required by the application purpose.

3.2. Localisation within RAMI 4.0

The scope and context of the software infrastructure are described using the reference architecture model RAMI 4.0, as defined by DIN in its specification 91345, and shown in Figure 1 [6].

The Digital Twin focuses on production resources that are stations – specifically work units – corresponding to the RAMI 4.0 nomenclature. The production resources are instances that are already deployed for use. The Digital Twin communicates descriptive and predicted parameters to software applications for production management, which mainly operate on work centre and enterprise level, but are potentially deployed cross-organisational in a connected world. To model the parameters, the Digital Twin integrates lower-level shop floor data acquired by control and field devices from the physical production resource.

The software infrastructure embodies the communication layer by providing data connections from shop floor data acquisition systems to production management applications and between Digital Twin components. The Digital Twin itself represents the information and the functional layer. As a precondition for the deployment of the infrastructure, shop floor data must be accessible from an integration layer, which provides the cyber-physical link between the shop floor and an IP network. The shop floor data is continuous, live, and often raw condition data in the form of time series data and discrete event logs [21]. In addition to sensory measurements, shop floor data can also be acquired through human input, especially for manually operated production resources.

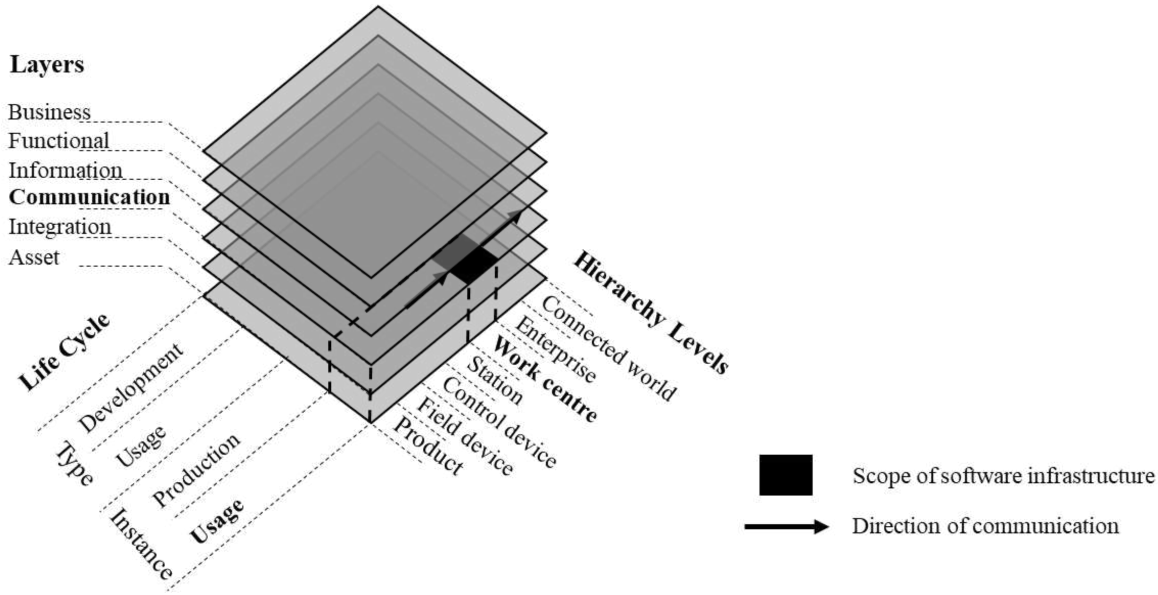

Figure 1. Localisation of the conceptualised software infrastructure within RAMI 4.0, figure adapted from [6]

3.3. IIoT Connectivity Stack

The data connections are described with reference to the IIoT Connectivity Stack as defined by the IIC [22]. It enhances the established TCP/IP reference model by the layers of connectivity frameworks and information to fully describe all required aspects of interoperability [16]. To ensure full semantic interoperability, interoperability standards define data models to make exchanged information directly usable among software applications with prebuilt APIs. Interoperability standards define underlying connectivity frameworks and build upon their provided syntactic interoperability. Connectivity frameworks define data formats and communication methods and enhance data connections by data integrity and security mechanisms. Connectivity frameworks rely on the technical interoperability established by underlying connectivity and networking protocols.

Figure 2 shows commonly used IIoT information, connectivity, and networking standards. On the highest level, OPC UA, the AAS, and MTConnect are relevant interoperability standards in the context of providing information from production resources. OPC UA defines its own proprietary connectivity frameworks, several of which enhance the SOAP framework. The UA Binary framework is an alternative for more efficient communication and relies on the UA TCP application protocol. MTConnect builds upon the REST framework. The AAS is also deployed with REST connections [23]. Like other web frameworks such as SOAP and WebSocket, REST typically utilises the application protocol HTTP, which relies on the transport protocol TCP. For asynchronous, lightweight data connections, MQTT can be deployed, e.g. when non-persistent condition data is communicated in unstable networks. An alternative is the lightweight CoAP protocol that uses the transport protocol UDP, which is more efficient in comparison to TCP at the cost of reliability. Controllers of automated production resources often provide acquired data through Ethernet fieldbuses, such as *Profinet*, *EtherNet/IP*, *Modbus/TCP*, and *EtherCAT*. All mentioned protocols use IP networks. Network access and the cyber-physical link are mostly provided by TSN/Ethernet, LAN, or 5G.

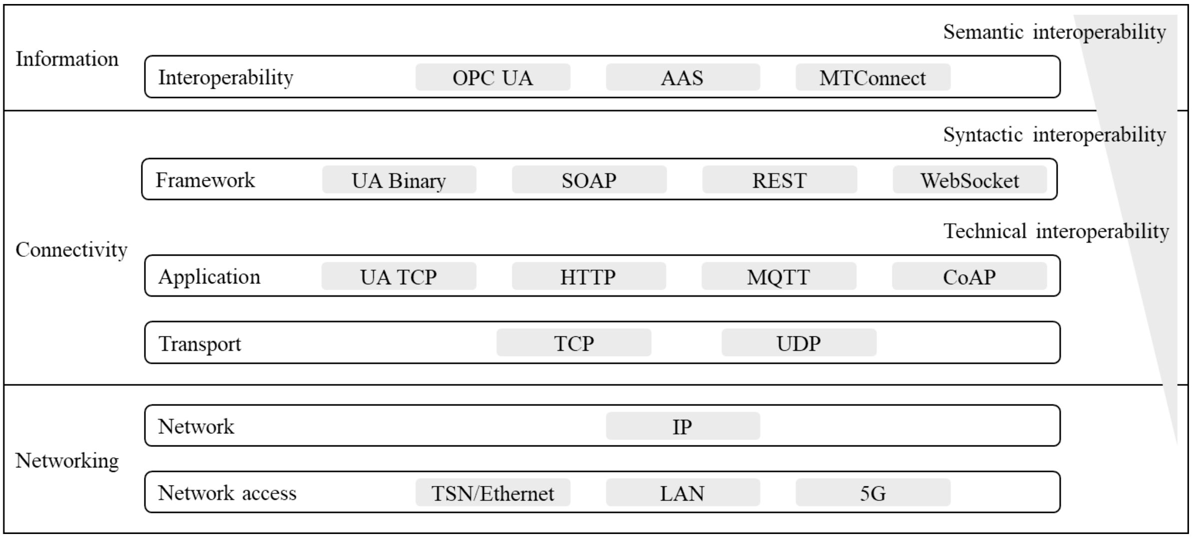

Figure 2. Allocation of relevant standards in the IIoT Connectivity Stack, adapted from [16] and [22]

3.4. Interoperability standards

MTConnect, OPC UA, and the AAS are interoperability standards in the context of IIoT and provide corresponding infrastructure for data connections between production resources and software applications. Table 1 shows the objects and the data in focus of each standard, as well as its Industry 4.0 communication capabilities [6].

Conceptualised as an adapter module, MTConnect mainly communicates uniform condition information unidirectionally from machine tools. OPC UA covers various industrial equipment like production machines, machine components, and transport modules. OPC UA focuses on a SOA-compliant, secure, and platform-independent exchange of live information.

The AAS provides a software infrastructure to describe static object characteristics, store historical data records, and retrieve knowledge from models through services that access linked data. In this context, OPC UA and MTConnect can embody the link to the shop floor and provide uniform condition data. Among the presented interoperability standards, the AAS encompasses the widest scope, including various industrial assets, such as production resources, products, parts, and software. The AAS also enables cross-organisational communication in a connected world envisioned by Industry 4.0.

Table 1. Interoperability standards in the context of IIoT

Interoperability standard	Connected objects	Provided data	Industry 4.0 communication
MTConnect	Machine tools	Live condition information	Active; unidirectional
OPC UA	Industrial equipment	Live and historical condition information	SOA-compliant; bidirectional
AAS	Industrial assets	Characteristics, models and knowledge, condition information, historical data records	SOA-compliant; bidirectional; cross-organisational

4. Conceptualisation

The software infrastructure is conceptualised to meet the following requirements:

- functional sufficiency,
- data security and reliability,
- application efficiency and performance, and
- development and maintenance efficiency.

Functional sufficiency, i.e., the provision of descriptive and predicted parameters, is reached through the integration of data storage and algorithm components required for data analytics-based Digital Twins as described in Section 3.1.

Data security and reliability are ensured by the connectivity framework of the AAS, which integrates mechanisms for authentication and data loss prevention [23]. Ideally, the shop floor data acquisition also entails such mechanisms, e.g. by providing data through OPC UA. Data security is additionally increased by limiting channels from the local shop floor network to the central layers – where the AAS server is deployed – to a single data connection. Dependency on network connection and bandwidth is reduced by transforming live data locally and temporarily storing records before communicating to the central AAS server.

Efficiency and performance when applying the Digital Twin, i.e., a low hardware capacity demand and a low response time, are improved by the local transformation of shop floor data. Shop floor data – especially when stemming from sensors – is often acquired as time series data with high frequency. The data volume to the central AAS server is reduced by only communicating and subsequently storing data records required for data analytics.

To lower the personnel effort and difficulty for development and maintenance, the proposed software infrastructure incorporates prebuilt and configurable components. It is widely applicable and reduces the need for various specific data connections and infrastructures. The following design principles enable this:

- For the provision of descriptive and predicted parameters, the software infrastructure follows the specification of the AAS, deploying a server that enables interoperability with production management applications. The AAS masks the heterogeneous production resources and unifies data access, both from a data connection and a data model perspective.
- The generic data analytics algorithms based on the generic record and parameter structure are integrated with the AAS, which allows for a prebuilt server.
- For the resource-specific data preparation, the connector to the shop floor and the data transformation algorithm are configurable. A shop floor integration platform is utilised that provides such components for interactive, visual configuration and minimises the required software coding. It supports commonly used data connection standards.
- The software infrastructure constitutes a mid-layer hub module that provides a singular data connection point for both shop floor data acquisition and software applications. The software infrastructure can be deployed across various resources, domains, and software applications.

Figure 3 outlines the proposed software infrastructure. The configurable shop floor client supports IIoT frameworks and protocols including OPC UA, MQTT, and CoAP. Additionally, Ethernet fieldbuses, including *Profinet*, *EtherNET/IP*, *Modbus/TCP*, and *EtherCAT,* are supported, as well as web frameworks such as REST, SOAP, and WebSocket. Databases and file servers that provide data through protocols like SQL over TCP/IP or FTP can also be connected. The shop floor integration platform is deployed in the local network of the production resource, e.g. an edge computing device. Such platforms are available as commercial as well as open-source software.

After the raw, resource-specific condition data is transformed into the generic, uniform structure defined by the AAS, it is communicated to the central AAS server and stored. Prebuilt data analytics algorithms retrieve the shop floor records and create descriptive or predictive models. The models' metadata is stored in the AAS of the production resource, such as influencing factors, the descriptive or predicted parameters, and the endpoint of the description or prediction service. The descriptive or predicted parameters are retrieved by production management applications from a dedicated service after getting the metadata from the AAS.

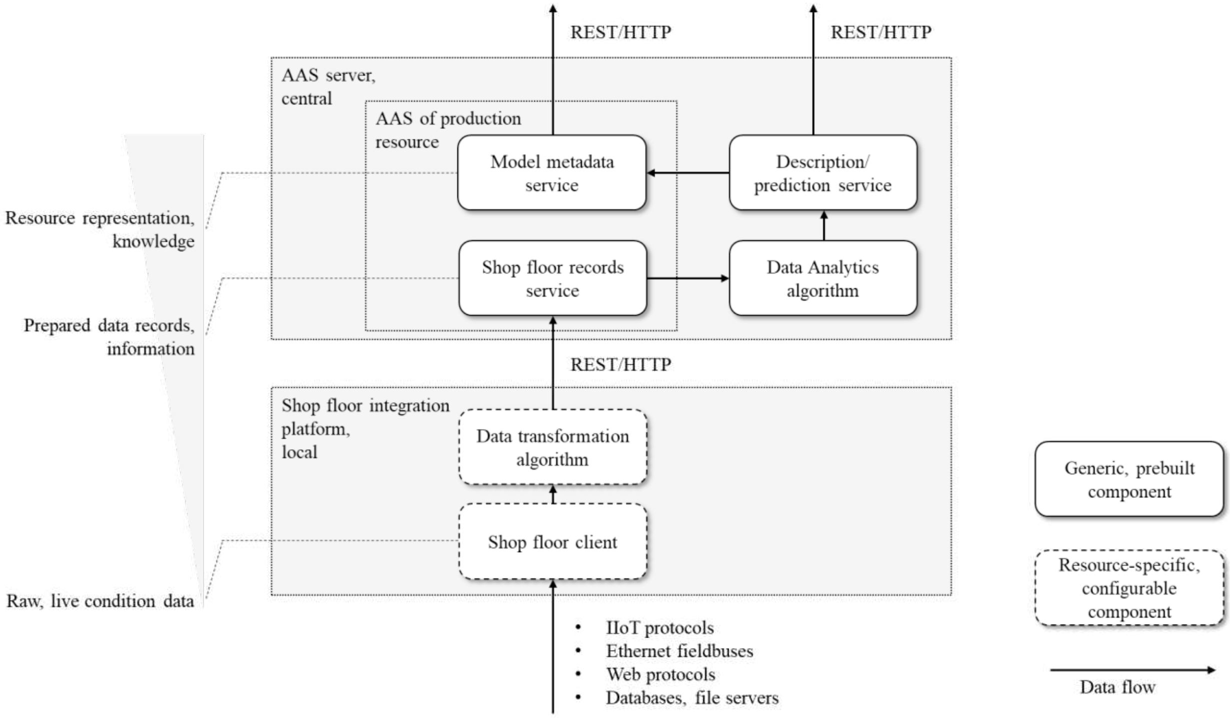

Figure 3. Software infrastructure for ready-to-use, data analytics-based Digital Twins of production resources

5. Demonstration

The proposed software infrastructure is demonstrated in a laboratory environment of a production research organisation. In the laboratory additive manufacturing machines are set up to study new material combinations and operating principles, and assembly robots are installed to develop Industry 4.0 use cases based on IIoT technologies.

As a functional scenario, the demonstrated Digital Twins provide models that predict parameters for capacity planning, which are used in a discrete event simulation. The data model is based on ISO standard 22400 [24], which is e.g. supported by OPC specification 40001-3 for shop floor data acquisition of machinery [25]. It defines the time elements of a production resource as setup time, production time, and delay time, and the throughput-related elements as good quantity and produced quantity. Based on these elements, uniform data records are stored for each production order, which are enhanced by influencing factors in a generic structure.

As a shop floor integration platform, the open-source platform *Node-Red* is deployed. Two production resources are connected. An articulated assembly robot with a mechanical gripper provides sensor data through OPC UA. A manufacturing machine, which performs powder-based selective laser melting, provides sensor data and program logs through MQTT. A flow of several configurable nodes allows for the required data connection and transformation, as shown in Figure for the assembly robot. First, data is mapped to the shop floor record structure defined by the AAS. The time series data is then aggregated to single values. For production, setup, and delay time this is the integral of the operating status of the robot. For the influencing factors, which are the product group, material, and weight, the value is static throughout one production order. A HTTP connector uses the AAS' REST/HTTP service to communicate and store the shop floor records in JSON format.

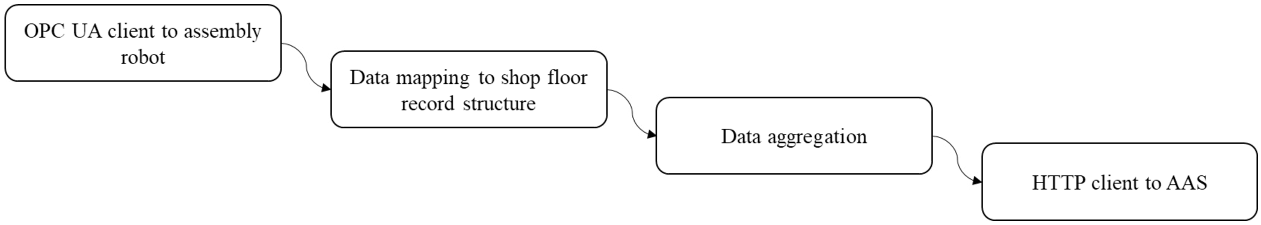

Figure 4. Configurable components: shop floor client and data transformation in Node-Red

The AAS is deployed using open-source *Eclipse BaSyx* components. The submodels of the AAS – as shown in Figure – were created following the procedure of [26]. The well-established, open-source Machine Learning algorithm *XGBoost* is deployed to create prediction models based on the production order records, mapping the dependencies of the predicted parameters to the recorded influencing factors. A service retrieves predictions from the model and provides the predicted parameters via REST/HTTP. The endpoint of the service is stored in the AAS of the production resource. The prediction service is called on demand by the discrete event simulation software *Plant Simulation* throughout its runtime. The discrete event simulation is deployed for capacity planning of the production resources and uses the predicted capacity parameters to determine the capacity demand of a planned production order sequence.

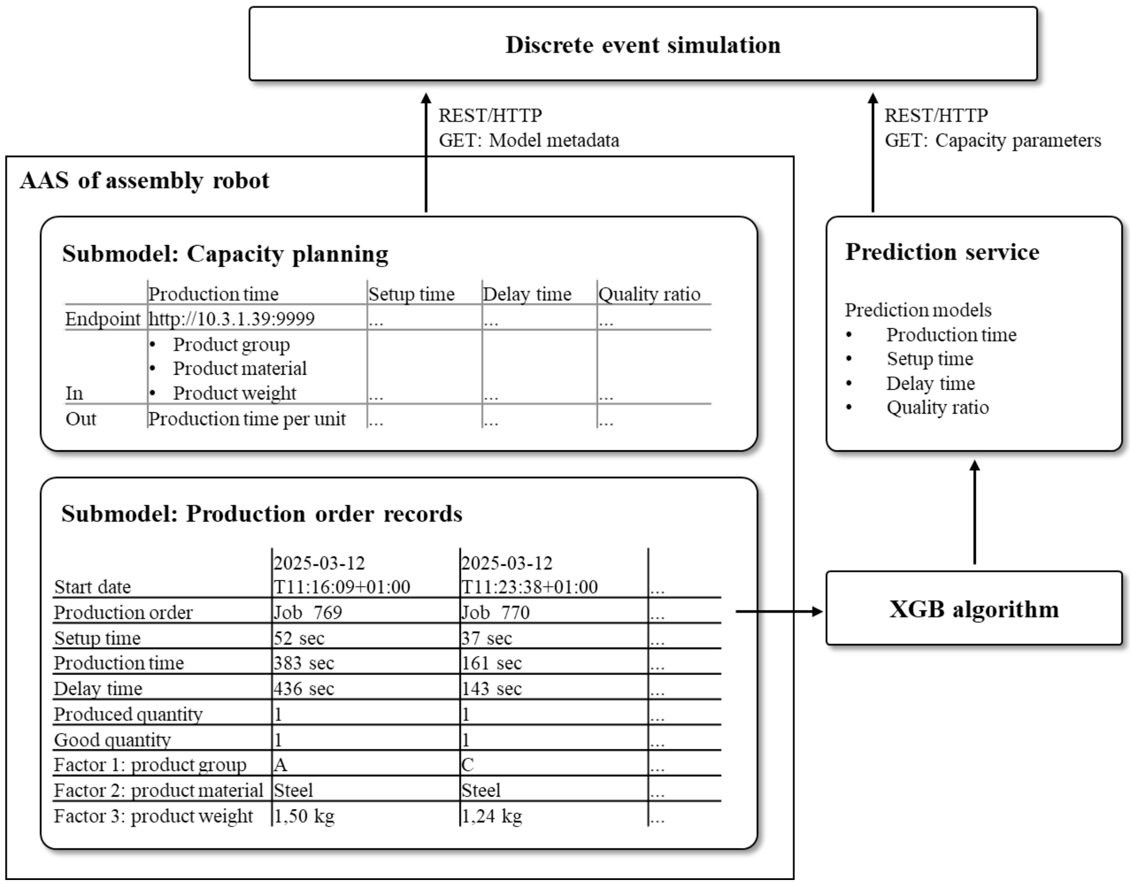

Figure 5. Prebuilt components: shop floor records, data analytics, and prediction service within the AAS server

6. Discussion

To assess whether the proposed infrastructure fulfils the requirements listed in Section 4, three semi-structured, standardised open-ended interviews were carried out. The interviewees are researchers in the field of IIoT, who are experts corresponding to the Dreyfus' skill model [27]. In addition, a focus group discussion was carried out at a production organisation that produces optical, photoelectronic, ultrasonic, and inductive sensors for industrial applications. The focus group consists of two proficient users of the Digital Twin, one expert developer of the Digital Twin, two expert developers of the corresponding software infrastructure, and one expert provider of the hardware infrastructure. For the focus group, a specific instance was implemented for demonstration using samples from the production organisation's raw shop floor data, and especially the AAS as an interoperability standard was discussed.

As a starting point, the interviews and discussion confirmed the list of requirements. The proposed infrastructure, with the design principles described in Section 4, was assessed as suitable for achieving functional sufficiency, data security, application efficiency and development efficiency. In addition, the following aspects were concluded:

- The data connection standards listed in Section 4 cover most of the shop floor data acquisition systems deployed in industrial applications. As a prerequisite for its deployment, the shop floor integration platform has to support these standards.
- OPC UA seems to establish itself as a standard to provide condition data from the shop floor. However – as proposed in this article – the AAS provides the more suitable infrastructure for incorporating data analytics and querying shop floor records. While OPC UA can store historical condition data, aggregated records and processed models are more suitably stored in central databases and file servers of the AAS, which can be administered with data backups and a scalable storage.
- As an alternative conceptual scenario separate AAS server of the proposed infrastructure would be obsolete if shop floor records, data analytics algorithms, and models are integrated into production management applications. However, this would constitute many-to-many data connections, whereas the AAS – as a mid-layer hub – reduces them to one per data acquisition system and software application. Additionally, the modular approach allows for consistency when the same records or models are used in several applications, e.g. for separate rough and detailed capacity planning. By that, the AAS avoids redundant data storage, processing, and communication. Moreover, the AAS fosters the establishment of vendor independent standardisation. It enables – as opposed to monolithic solutions – specialised applications, e.g. by separating production management tasks from data analytics.

It should be noted that assessing the infrastructure's performance on the demonstration instance is limited. E.g, the discrete event simulation utilises only one Digital Twin and has not been stress-tested. Retrieving values from the Digital Twin is time-critical in particular for near real-time decision-making and production control. A simulation or optimisation procedure may have to retrieve a multitude of predictions in a multitude of simulation runs or optimisation steps.

The infrastructure is demonstrated using *Node-Red*, where the integration of the open-source environment *Apache Spark* would offer additional configurable data transformation components, further reducing the amount of coding required. In comparison, commercial shop floor integration platforms may be more tailored to production environments. They may realise a higher performance and include advanced features of professional software development, like quality assurance and deployment mechanisms.

7. Conclusion and outlook

The proposed software infrastructure is conceptualised to enable ready-to-use Digital Twins. It incorporates prebuilt components for descriptive and predictive data analytics and facilitates resource-specific data preparation through a local platform with configurable components. The AAS as a modular mid-layer hub provides a single, uniform data access point for production management applications to retrieve information about the resource. The generic deployment of the interoperable infrastructure reduces specific developments and data connections.

The article encourages further standardisation efforts, specifically to increase AAS submodel specifications. This would reduce heterogenous data models and the necessity of developing specific data transformation. With the AAS building upon OPC UA as a data source, the alignment of their standardisation efforts holds potential to increasingly utilise prebuilt components. E.g. an AAS submodel for shop floor records that follows ISO 22400 – as described in the demonstration case – could directly align with OPC UA 40001-3 for machinery. In addition, a submodel template for data analytics models and respective services has promise for further unification and prebuilt components.

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References

[1] Demke, T. M., Hiller, T., Welzel, K., Steffens, C., Mundt, C., Alieksieiev, V., Fulterer, J., Maetschke, J., Kuhn, C., Kalchschmid, V., Luber, M. (2024 "Status Quo on Production Planning and Control".
[2] ISO 23247 "Automation systems and integration - Digital twin framework for manufacturing".
[3] Ivanov, D. (2024 "Conceptualisation of a 7-element digital twin framework in supply chain and operations management" *International Journal of Production Research* 62: S.2220.
[4] West, T. D., Blackburn, M. (2017 "Is Digital Thread/Digital Twin Affordable? A Systemic Assessment of the Cost of DoD's Latest Manhattan Project" *Procedia Computer Science* 114: S.47.
[5] Luber, M., Wagner, S., Wegmann, M., Schilp, J. (2025 "Concept of a plug-and-play, Machine Learning Digital Twin of the production resource for Detailed Capacity Planning and Scheduling" *Procedia Computer Science* 253: S.1266.
[6] Deutsches Institut für Normung (2016 "Referenzarchitekturmodell Industrie 4.0 (RAMI4.0), Berlin", Beuth Verlag GmbH (DIN SPEC 91345:2016-04).
[7] Marosi, A. C., Emodi, M., Hajnal, Á., Lovas, R., Kiss, T., Poser, V., Antony, J., Bergweiler, S., Hamzeh, H., et al. (2022 "Interoperable Data Analytics Reference Architectures Empowering Digital-Twin-Aided Manufacturing" *Future Internet* 14: S.114.
[8] Ionuţ, L., Theodor, B., Silviu, R. (2024 "Design of a Data Collection System for Robot Digital Twins", in *Advances in Service and Industrial Robotics*, Springer Nature Switzerland, Cham: 463–471.
[9] Nölle, C., Arteaga, A., Egia, J., Salis, A., Luca, G. de, Holzknecht, N. (2022 "Digital Twin-enabled Application Architecture for the Process Industry", in *Proceedings of the 3rd International Conference on Innovative Intelligent Industrial Production and Logistics*, SCITEPRESS - Science and Technology Publications: 255–266.
[10] Leinenbach, A., Wagner, M., Oettl, F., Schilp, J. (2024) "*The Process Data Twin For Digitized Production*", Hannover publish-Ing.
[11] Ding, K., Chan, F. T., Zhang, X., Zhou, G., Zhang, F. (2019 "Defining a Digital Twin-based Cyber-Physical Production System for autonomous manufacturing in smart shop floors" *International Journal of Production Research* 57: S.6315.
[12] Shao, G., Kibira, D. (2018 "Digital Manufacturing: Requirements and Challenges for Implementing Digital Surrogates", in *2018 Winter Simulation Conference (WSC)*, IEEE: 1226–1237.
[13] Da Silva, J. T., Dias, A. L., Da Silva, I. N. (2023 "A Survey on OPC UA Protocol: Overview, Challenges and Opportunities", in *2023 15th IEEE International Conference on Industry Applications (INDUSCON)*, IEEE: 1523–1530.
[14] Bong Kim, D., Shao, G., Jo, G. (2022 "A digital twin implementation architecture for wire + arc additive manufacturing based on ISO 23247" *Manufacturing Letters* 34: S.1.
[15] Beregi, R., Pedone, G., Háy, B., Váncza, J. (2021 "Manufacturing Execution System Integration through the Standardization of a Common Service Model for Cyber-Physical Production Systems" *Applied Sciences* 11: S.7581.
[16] Göppert, A., Grahn, L., Rachner, J., Grunert, D., Hort, S., Schmitt, R. H. (2023 "Pipeline for ontology-based modeling and automated deployment of digital twins for planning and control of manufacturing systems" *Journal of Intelligent Manufacturing* 34: S.2133.
[17] Miny, T., Heppner, S., Guo, W., Möller, L., Kleinert, T. (2023 "Standardized Integration of Source Systems into Asset Administration Shell Realizations", in *2023 IEEE 21st International Conference on Industrial Informatics (INDIN)*, IEEE: 1–6.
[18] Ye, X., Hong, S. H., Song, W. S., Kim, Y. C., Zhang, X. (2021 "An Industry 4.0 Asset Administration Shell-Enabled Digital Solution for Robot-Based Manufacturing Systems" *IEEE Access* 9: S.154448.
[19] Schmid, J., Sommer, L., Ramos, J., Guo, X. (2024 "Concept of hybrid-modelled digital twins for energy optimisation and flexible manufacturing systems for SMEs" *Procedia CIRP* 130: S.711.
[20] Shin, S.-J., Um, J. (2024 "Deploying data analytics models in asset administration shells: Energy prediction in manufacturing" *Engineering Applications of Artificial Intelligence* 138: S.109269.
[21] Liu, C., Su, Z., Xu, X., Lu, Y. (2022 "Service-oriented industrial internet of things gateway for cloud manufacturing" *Robotics and Computer-Integrated Manufacturing* 73: S.102217.
[22] Schneider, S., Joshi, R. (2017) "*A Practical Guide to Using the Industrial Internet Connectivity Framework"*.
[23] Industrial Digital Twin Association "Specification of the Asset Administration Shell: Application Programming Interfaces (01002-3-0-4).
[24] ISO 22400 "Automation systems and integration - Key performance indicators (KPIs) for manufacturing operations management".
[25] OPC Foundation "Machinery Job Management (40001-3).
[26] Wittmann, L., Luber, M., Philipp, S., Schilp, J. (2025 "Application of the asset administration shell for mapping a modular and connected robot system – System architecture of a digital twin for a robot system" *wt Werkstattstechnik online* 115: S.141.
[27] Dreyfus, S. E. (2004 "The Five-Stage Model of Adult Skill Acquisition" *Bulletin of Science, Technology & Society* 24: S.177.