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Standardisation in Digital Twin Architectures in Manufacturing

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***Abstract*—Engineering digital twins following standardised reference architectures is an upcoming requirement for ensuring their adoption and facilitating their creation, processing, and integration. The ISO 23247 standard proposes a reference architecture for digital twins in manufacturing, including an entity-based reference model and a functional view specified in terms of functional entities. During our experience with projects in the field, we noticed that standards, and in particular the ISO 23247 standard, are not completely followed. In this paper, we analyse to what extent digital twin architectures documented in the literature are aligned with the reference architecture presented in the ISO 23247 standard. We achieved this through a mixed-methods research methodology that includes the analysis of 29 digital twin architectures in the manufacturing domain resulting from a systematic literature review of 140 peer-reviewed studies, a survey with 33 respondents, and four semi-structured, in-depth expert interviews. On the basis of our findings, practitioners and researchers can reflect, discuss, and plan actions for future research and development activities.**

***Index Terms*—Software Architecture, Digital Twin, ISO 23247, Reference Architecture**

I. Introduction

In the manufacturing domain, Digital Twin (DT) is a key enhancer for transforming traditional manufacturing into smart manufacturing. The idea of DT is to use digital technologies to create software (virtual) replicas of physical processes and assets to enable, e.g., smart monitoring, analysis of decisions, prediction of potential risky actions, and controlling manufacturing assets. DT systems are intrinsically complex in their nature and the lack of guidelines makes difficult for corporation to adopt them [1]. Engineering DTs following standardised reference architectures is an upcoming requirement for ensuring their adoption and facilitating their creation, processing, and integration [2]. Reference architectures (RAs) are the cornerstone of the successful development of complex software-intensive systems such as DTs [1]. RAs aggregate knowledge and design expertise, inspiring software architects to develop more detailed software architectures in multiple contexts [3] [4]. Martinez-Fernández calculated a three-year return on investment of 42% with a payback period of 16.5 months for software companies adopting RAs [5]. Many industrial sectors used RAs successfully in recent years, including automotive [6], avionics, and robotics.

During our experience within different collaborative research projects, we found out that several multinational corporations struggled with adopting DT systems and were seeking guidance for their realisation. For example, a German multinational automotive parts manufacturing company was facing challenges in navigating the complex set of functionalities and procedures needed to realise DTs. A Swedish multinational manufacturing company struggled to accelerate the creation of value-chains across enterprise boundaries. To address these and further challenges, corporations started to explore standardised solutions such as the International Organization for Standardization (ISO) 23247 standard for DTs in manufacturing. The ISO 23247 standard was introduced in 2021 and includes a RA that identifies functionalities of DTs in manufacturing and encapsulates them in so-called functional entities (FE). In this regard, the standard provided to the corporations with transparency and critical guidance in the choice of the implementation procedures and related technologies [7] [8]. Within this frame of reference, being aligned with the ISO 23247 RA is perceived as pivotal for tackling technical challenges that no single organisation can solve on its own, and for defining a context where different architectures can be compared and analysed. Nevertheless, being compliant with a RA is not a trivial task and requires advanced resources.

In light of these premises, the Research Goal (RG) of this work is *to evaluate to what extent state of the art software architectures for DTs in manufacturing are aligned with the ISO 23247 RA*. In other words, we check to what extent state of art software architectures for DTs in manufacturing implement the FEs identified by the ISO 23247 RA (or similar ones). Furthermore, we check if current state of the art architectures implement additional functionalities not captured by the FEs of the standard.

We addressed the above goal using a mixed-methods research methodology. In particular, we analysed 29 DT architectures targeting the manufacturing domain resulting from a systematic literature review of 140 peer-reviewed studies, performed a survey with 33 respondents, and conducted four semi-structured, in-depth expert interviews. The mixed-methods methodology helped us in collecting both quantitative and qualitative data through the systematic review and survey, and the interviews, respectively. In addition, it helped us in minimising validity threats related to single method limitations [9]. The systematic review helped us collect data that we used to tackle the above RG, hence identifying the misalignment. The survey and expert interviews helped us to shed light on: (i) the importance of being aligned with the RA, (ii) the reasons for misalignment and the extent to which such a misalignment should be restored.

Our study examines the existing misalignment between state of the art DT architectures and ISO 23247 RA. Expressly, we point out which of the FEs of ISO 23247 are not implemented in current architectures and discuss possible reasons for the lack of implementation with experts in the field. Furthermore, we identify functionalities not captured in the ISO 23247 RA but implemented in current architectures.

On the basis of our findings, practitioners and researchers can reflect, discuss, and plan actions for future research and

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development activities. In addition, we believe that this work can help in gaining early insights into the ISO 23247 RA, understanding the progress of standardisation efforts and the acquired awareness can then be used to shape a possible evolution of the ISO 23247 RA. In fact, it is expected for the ISO 23247 RA to gradually evolve through an iterative feedback process [10]. In this way, we hope that we will contribute towards *"maturing the DT concept in manufacturing from infancy to a value-generating tool that improves production processes and operations*" [7].

The remainder of this paper is as follows. Section II presents an overview of the ISO 23247 RA. Section III details the adopted research methodology to enable independent verification and replication of this research. In addition, it elaborates on how we mitigated threats to validity. Section IV presents and discusses the answers to the RQs of this work. Section V describes the validation activities and elaborates on the results of the survey and interviews. Section VI gives an overview of related works. Eventually, Section VII concludes the paper with final remarks and future works.

II. Digital twin in manufacturing and ISO 23247

A recent survey on definitions of DT in the production domain reports on more than ten different definitions of DT [11]. Our work adopts the DT definition given in the ISO 23247 standard, which describes *"a digital twin in manufacturing as a fit for purpose digital representation of an observable manufacturing element with synchronisation between the element and its digital representation [...] it exists across the entire product life cycle and [...] improves the performance of the manufacturing system" [12].*

ISO 23247 provides a standardised framework that can assist manufacturers in developing case-specific implementations of DTs. The ultimate goal of this standardisation effort is to provide guidelines, methods, and best practices to facilitate the *composability* and *interoperability* of DT solutions in the manufacturing domain. The standard consists of four parts. Part two defines a *reference architecture* for DTs in manufacturing (Figure 1) and includes (i) an entity-based *reference model* and (ii) a *functional view* of the entity-based reference model with specified FEs. The RA serves as a guide for facilitating DT implementation for different stakeholders, including users, application developers, and device manufacturers. The entity-based reference model uses a segmented layered pattern with sidecar[1] of four main layers (entities): Device Communication, Digital Twin, User, and Cross-System entities (grey boxes in Figure 1). Each entity has an arbitrary number of sub-entities (grey boxes in Figure 1). The Device Communication entity is divided into two sub-entities and is responsible for collecting data from the Observable Manufacturing Elements (OMEs) and controlling the OMEs. The standard defines OMEs as items that have physical presence or operation in manufacturing (e.g., products, processes, equipment) [12]. The Digital Twin entity is composed of three sub-entities and is responsible for modelling the data collected from the Device Communication entity and providing functionalities such as realization, management,

[1]We refer to the definition of segmented layered pattern with sidecar provided by Bass et al. in [13]

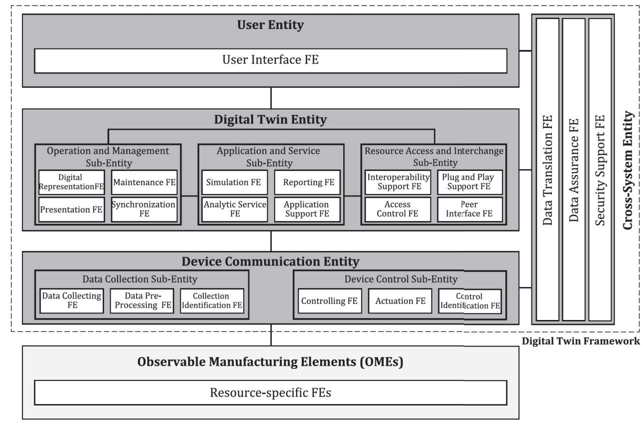

Figure 1: ISO 23247 RA [12].

synchronisation, and simulation. The User entity uses the services provided by the Digital Twin entity and hosts the application of the framework. The Cross-System entity spans across all the other entities to provide common functionalities such as security and data translation assurance.

In addition to the entity-based reference model, the standard provides a functional view that composes of FEs (white boxes in Figure 1) refining the entities of the reference model into functionalities to be implemented by DT applications. The standard recommends that a DT implementation realises all the following FEs (or similar ones) [12]. *Collection identification* identifies data needed from OMEs. The data are collected by *Data collecting* and pre-processed (e.g., filtered, aggregated) by *Data pre-processing*. *Control Identification* uniquely and unambiguously identifies an OME to be controlled. This is controlled using *Controlling* that sends proper commands to the OME. *Actuation* actuates an OME as a response to a request from the user or the digital twin entities. *Digital representation* models the information from an OME to represent its, e.g., physical characteristics and status. *Presentation* displays information in an appropriate format (e.g., text, images, charts, video) to be processed by a human-machine interface (HMI). *Maintenance* keeps DTs operational (e.g., monitoring results, identifying errors, repairing anomalies) while *Synchronisation* synchronises the status of a DT and its corresponding OME. *Simulation* predicts the behaviour of the OME. *Analytic service* manages and analyses data collected from OMEs and from Simulation. Data from simulation, analytic service, or production results are reported by *Reporting*. *Application support* provides services for implementing, e.g., predictive and reactive maintenance, applications. *Interoperability support* enables integration between DTs and other systems, such as Enterprise Resource Planning (ERP) systems. *Security support* provides authentication, authorisation, confidentiality, and integrity to the DT. *Access control* controls and accesses the user entity in conjunction with the security support FE. *Data translation* and *Data assurance* supports the translation (e.g., protocol conversion, syntax adaption) of the exchanged data among entities and ensures the accuracy and integrity of data in conjunction with security support FE, respectively. *Plug and*

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play support enables the dynamic connection of an OME to its DT. *Peer interface* and *User interface* provide interfaces to other DTs and interfaces between the user entity to the digital twin entity, respectively. Following the ISO 23247 recommendation, in this work, we assessed the alignment of current software architectures for DTs documented in the literature with respect to the functional reference architecture proposed in the standard.

III. Research Methodology

We carried out this work by employing a mixed-methods research methodology that we developed based on a set of complementary research methods to compensate for single method limitations [14]. In particular, we used the guidelines on systematic review by Kitchenham and Brereton [15], on survey by Kasunic [16], and on interviews by Shull et al. [14]. The systematic review helped us in collecting data that we used for answering the identified RG, hence identifying the misalignment. The survey and the interviews helped us in gaining qualitative insights on the importance of being compliant with the RA in the standard, the reasons for the misalignment, and to what extent such a misalignment should be restored. Besides, they helped us in validating the results from the literature review. Figure 2 illustrates the process we followed, which consists of three main phases: (i) *planning*, (ii) *conducting*, and (iii) *documenting*.

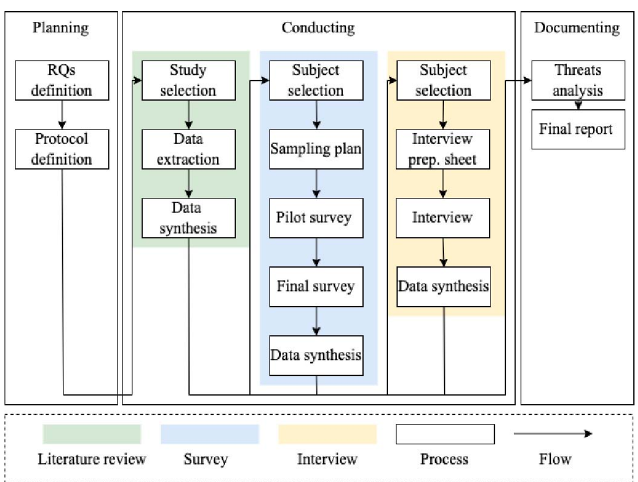

Figure 2: Overview of the research methodology.

A. Planning

In the planning phase, we identified the need to conduct this study and formulated the overall RG and related research questions (RQs). The RG is *to evaluate to what extent state of art software architectures for DTs in manufacturing are aligned with the ISO 23247 RA*. We broke down the above RG into two RQs:

RQ 1 To what extent do current software architectures implement the functional entities of ISO 23247 RA?

RQ 2 Are there functionalities implemented by current software architectures not captured by any functional entity of the ISO 23247 RA?

Afterward, we defined the protocol to be followed by all the researchers to carry out the study systematically. The main output of this phase was a detailed protocol reviewed by all the authors and consisting of a set of steps for performing a systematic review, a survey, and interviews.

B. Conducting

In the conducting phase, we performed a systematic review, a survey, and interviews following the 12 steps defined in the research protocol. To validate the synthesised data from the literature review and complement them with qualitative insights, we proceeded with a two-step process consisting of a survey and expert interviews.

1) Literature review: in the *study selection* step, we selected peer-reviewed studies that proposed DT architectures within the manufacturing domain. To this end, we started from the set of 140 studies identified in our previous systematic study on DT architectures [1]. Due to space constraints, we have omitted details about the search and selection process for the initial 140 studies. Interested readers can find all the details in our prior study [1]. We further filtered the initial set of studies using the following inclusion criteria:

- Studies proposing a DT architecture targeting the manufacturing domain.
- Studies proposing a DT architecture with identifiable and well-documented components.

Following the selection process proposed by Ali et al., we only selected those studies that satisfied all the inclusion criteria [17]. This helped us in discarding those studies that were not focusing on the manufacturing domain or that had a vague description of their architecture and components. Hence, they helped us minimising possible threats to validity. The final set comprised 29 primary studies, out of which 11 were co-authored by at least one practitioner and/or described industrial DTs. In the *data extraction* step, we extracted data from the selected studies using an extraction framework purposely built [15]. The extraction framework composes of two main parts. The first part contains the list of the 23 entities described in the ISO 23247 standard. The second part would collect the actual components of the DT software architectures described in the studies to realise that functionality. Using the extraction framework, we thoroughly examined the selected studies to identify the components defined in the architectures and mapped them to the entities of the standard. To this end, we used the component descriptions in the studies and the entity definitions in the standard. Authors independently performed the mapping according to their understanding of the components description in the studies and the definition of FEs in the standard. In the event of uncertainties, annotations and comments were added to the data extraction form, which were further discussed in plenary meetings to reach a consensus. In the *data synthesis* step, we used the guidelines by Cruzes et al. and elaborated on the extracted data to provide answers to our research questions [18]. In this research, we used vertical analysis of the data to present statistical evidence for each question. Section IV presents and discusses the outcome of the systematic literature review. The selection sheet, the primary studies, the extraction form, the extracted and synthesised data are available in the

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replication package[2].

2) Survey: we conducted the survey following the process proposed by Kasunic [16]. The survey has four main objectives aligned with the RQs, which are:

- For all the FEs of the RA not considered by current architectures, understanding the reasons why they are not considered and their needs in architectures for DTs.
- Discussing the frequency of FEs considered by current architectures.
- For all the functionalities not captured by FEs of the ISO 23247 RA, understanding whether the RA should be extended with FEs capturing these functionalities.
- Understanding the importance of being aligned with the RA in the standard.

In the *subject selection* step, we first identified the target audience and then analysed the audience characteristics as a vital step to create questions that utilise the appropriate terminology. The identified target group is composed of: (i) academics with expertise in software architecture and DT and (ii) professionals from corporations that adopted or are in the process of adopting DT in manufacturing. In the next step, we designed the *sampling plan*. Hence we determined the target group size and how individuals will be selected for the survey. To this end, from the 19th of August 2022 to the 6th of October 2022, we contacted: (i) 58 authors of the selected primary studies, (ii) members of relevant groups on LinkedIn[3], (iii) 43 researchers and practitioners in our network. In total, we collected 33 responses. Next, we designed and developed the questionnaire by deciding: (i) what questions to ask, (ii) the type of questions to be asked, (iii) the sequence of questions, and (iv) the overall layout of the questionnaire. We built the survey using Google Forms[4], mainly using close-ended (evaluation type) questions. In accordance with the guidelines [16], we grouped the questions into three main categories: (i) demographic information to gain an understanding of the characteristics and circumstances of respondents, (ii) substantive questions which address the objectives of the survey, and (iii) feedback and comments from respondents. In the *pilot survey* step, we conducted a pilot test survey. Using a small group of the target audience composed of 9 respondents, we simulated the survey implementation in order to evaluate whether the questions were understandable to the audience and whether the survey objectives were meaningful. Afterward, we redesigned the survey based on the feedback. In particular, we changed a dichotomous question (yes or no) to a linear scale question, added free text paragraphs to enable respondents to leave remarks, and added a question on the potential reason for the misalignment. We distributed the *final survey* to the selected target group and set the timeline for follow-up reminders. We send two reminders in the two subsequent weeks after distributing the survey. In the *data synthesis* step, we synthesised and analysed the results using descriptive statistics [19], and open coding and constant comparison techniques from Grounded Theory [20]. We used the former for closed-ended questions and the latter for open ones. We presented the results graphically. Section V presents and discusses the survey results. The pilot survey, the final survey, and the related answers are available in the replication package [2].

3) Interviews: we conducted four semi-structured, in-depth interviews following the guidelines by Shull et al. to complement the findings of the survey and gather more qualitative insights from the respondents [14]. In the *subject selection* step, we selected the experts based on their experience with DT-based systems and ISO 23427 standard from the pool of survey respondents. The experts that we interviewed have the following profiles:

- Deputy head of an industrial automation institute in a German university.
- Two co-founders of an international corporation that provides standard-based solutions for product and asset life-cycle management.
- Active participant in ISO standards for more than 30 years and Director of the defense and aeronautics department in a Norwegian SME that develops standard-based software to resolve data interoperability.

The participants received the *interview preparation sheet* before the interview meeting. It included the purpose of the meeting, its expected duration, a detailed schedule, and the measures we took to ensure privacy and confidentiality. All the interviews were held online using the Microsoft Teams platform [5]. The duration of the *interviews* was between 50 and 60 minutes. To ensure anonymity, unbiased answers, privacy, and confidentiality, as well as to minimise possible validity threats, we collected the participant answers using an online tool simulating sticky notes called Padlet[6]. The questions were based on the respondents' survey answers and focused on (i) those answers that were not aligned with average respondents' answers or (ii) those answers that needed more clarification. During the first half of the meeting, the respondents wrote their answers in the Padlet. We reserved the second half of the meeting for further discussion on each question and final remarks. Lastly, in the *data synthesis* step, we synthesised the results from the interviews and reported them in the documenting phase. Section V discusses the insights gained during the interviews. The Padlet sheets from each interviewee are available in the replication package [2].

C. Documenting

In the documenting phase, we reported on the threats to validity and related mitigation strategies and wrote the final report. We reported on the results obtained from the data synthesis of the literature review, survey, and interviews. To enable independent verification and replication of this study, we provide a complete and public replication package [2]. The replication package contains the artefacts and the data from all the phases of our research methodology.

[2]The replication package is available at: https://anonymous.4open.science/r/ICSA2023/README.md

[3]Digital Twin for Production, Manufacturing and Logistic https://www.linkedin.com/groups/12531344/, Digital Twin https://www.linkedin.com/groups/13543070/, Customer Experience, Intelligent Automation, Digital Twin https://www.linkedin.com/groups/3707199/

[4]https://www.google.com/forms/about/

[5]https://www.microsoft.com/en-ww/microsoft-teams/

[6]https://padlet.com/

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We carried out this research according to well-established guidelines for empirical studies in software engineering, including systematic studies [15], surveys [16] and interviews [14]. In the following, we describe the main threats to validity according to the scheme by Wohlin et al. [9] and elaborate on mitigation strategies.

Internal validity threats are primarily associated with the design of the study and refer to the degree to which claims are supported by the obtained data [9]. We mitigated these threats to validity by defining a research protocol to conduct this study employing well-established guidelines for systematic studies, surveys, and interviews on software engineering. All authors reached a consensus while developing and validating the protocol. To further mitigate internal threats to validity related to data analysis and synthesis, we employed rigorous descriptive statistical methods for data analysis [19] [20]. In addition, we distributed surveys to experts in the field to validate the obtained data. To mitigate the risk of fishing for results, we constructed the survey based on the model for evaluating the rigor and relevance of research presented by Ivarsson et al. [21]. We used a mix of close-ended and open-ended questions to keep the respondents focused and motivated. As a result of the above tasks, we were able to identify and resolve potential issues regarding the consistency of the extracted data.

Construct validity threats focus on the relation between the theory and the observation [9]. We are confident that the selected primary studies are representative of the population defined by the research questions since we followed a well-defined and validated protocol. We further mitigated the risks associated with data extraction by defining a framework based on the list of functional entities defined in the standard. Each author repeated the process of extracting data from the studies individually. In the event of doubts, authors added annotations to the respective primary studies and discussed upon reaching a consensus. A possible threat related to the survey is hypothesis guessing or confirmation bias, happening in case respondents adjust their answers with the main goal of the study. In order to mitigate such a threat, we posed the questions objectively and used references to relevant sources.

External validity threats relate to the generalisability of the final observed results and outcomes of the study [9]. The main concern that can impact external validity in our research is whether the set of primary studies is representative of state of the art and practices of DT architectures in manufacturing. To mitigate this threat, we selected our primary studies from the pool of papers resulting from our systematic mapping study on DT architecture [1]. In our previous mapping study, the initial search was conducted in four different electronic databases in software engineering, which was complemented with a fully recursive snowballing activity. Further, we filtered only those studies that propose a DT architecture in the manufacturing domain and have well-documented components for their architecture. It is worth noting that we decided to define and apply the second inclusion criteria when evaluating the primary studies from all authors. This is due to the fact that some architectures had vague descriptions of their components. The final set of primary studies comprised 29 studies, of which 11 described industrial DTs and/or were co-authored by at least one practitioner.

Conclusion validity threats refer to the relationship between the extracted data and the obtained findings, and they reflect the credibility of the conclusions drawn from the extracted data [9]. In general, we mitigated potential threats to conclusion validity by rigorously applying best practices from systematic studies and survey guidelines. More specifically, we have documented every step of our research and provided a public replication package to ensure transparency and replicability. In addition, we reduced potential bias during the data extraction process by using an extraction form based on well-established taxonomies defined by the ISO 23247 standard. All authors participated in data extraction, analysis, and synthesis steps. We have also taken measures to mitigate other threats, such as lack of expert evaluation and fishing for results. As a precaution, we conducted expert interviews only with experienced and proven profiles to omit the contamination of the validation process with our expectations. Lastly, we drew our conclusions based on available evidence and clearly labeled the hypotheses arising from the survey respondents and the interview discussion.

IV. Results

In this section, we present the literature review findings to answer the identified RQs. Section IV-A elaborates on the extent that FEs of the ISO 23247 RA are considered by current software architectures (RQ1). Section IV-B describes functionalities implemented by current architectures and not captured by any FE of ISO 23247 RA (RQ2).

A. FEs implemented by current software architectures (RQ1)

To provide answers to this research question, we thoroughly examined the selected studies to map their components to the entities of the standard. To this end, we used the component descriptions in the studies and the entity definitions in the standard. Table I summarises the synthesised data. The first column lists all the functional entities of the RA. The second column provides the percentage and absolute number of primary studies addressing each FE. The third column contains the references to the respective studies.

The first thing that we observed is that current software architectures only implement limited number of FEs depending on their purposes and definitions. Data collecting is the only FE considered by all the studies, while other FEs are considered by a percentage of studies comprised between 0 and 69%. When observing FEs that are addressed by a limited number of studies, we noticed that Maintenance and Security support FEs are considered by only 41% and 21% of the studies, respectively. Shukla proposes an example of an architecture that incorporates both Security and Maintainability FE at al [P24]. They integrate blockchain to fulfill the need for security and data traceability. In addition, they build services related to fault detection and prediction to ensure maintainability. The lack of implementation for Maintenance and Security FEs suggests that current DT architectures primarily focus on the functional capabilities of the system rather than on its qualities, such as maintainability and security. Controlling and Actuation FEs are considered by 17% of the studies only. Zheng et al. describe an architecture that incorporates a control mode where the user input is received by a DT API and control signals are sent to the physical machines [P2]. In current literature, systems

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Functional entities	% (#)	Papers
Data collecting	100% (29)	[P2], [P10], [P12], [P15], [P20], [P21], [P27], [P28], [P1], [P6], [P8], [P9], [P13], [P16], [P18], [P23], [P24], [P25], [P26], [P29], [P3], [P4], [P5], [P7], [P11], [P14], [P16], [P19], [P22]
Data pre-processing	55% (16)	[P2], [P12], [P20], [P21], [P28], [P8], [P16], [P23], [P24], [P25], [P4], [P7], [P11], [P14], [P16], [P19]
Collection-Identification	59% (17)	[P2], [P10], [P20], [P27], [P28], [P1], [P6], [P8], [P16], [P18], [P23], [P25], [P29], [P3], [P4], [P7], [P19]
Controlling	17% (5)	[P2], [P18], [P23], [P25], [P19]
Actuation	17% (5)	[P2], [P18], [P23], [P25], [P19]
Control-identification	17% (5)	[P2], [P18], [P23], [P25], [P19]
Digital representation	72% (21)	[P2], [P10], [P12], [P20], [P28], [P6], [P9], [P16], [P18], [P24], [P25], [P26], [P29], [P3], [P4], [P5], [P7], [P11], [P14], [P16], [P19]
Presentation	59% (17)	[P2], [P1], [P6], [P8], [P13], [P16], [P23], [P25], [P29], [P3], [P4], [P5], [P7], [P11], [P14], [P16], [P19]
Maintenance	41% (12)	[P2], [P12], [P6], [P13], [P16], [P24], [P25], [P26], [P4], [P7], [P14], [P16]
Synchronization	41% (12)	[P2], [P10], [P12], [P1], [P6], [P16], [P18], [P25], [P3], [P4], [P5], [P14]
Simulation	59% (17)	[P2], [P15], [P21], [P6], [P8], [P13], [P16], [P18], [P23], [P24], [P25], [P3], [P4], [P5], [P11], [P14], [P22]
Analytic service	69% (20)	[P2], [P10], [P12], [P20], [P27], [P1], [P6], [P8], [P16], [P18], [P23], [P24], [P25], [P3], [P4], [P5], [P7], [P11], [P14], [P22]
Reporting	52% (15)	[P2], [P10], [P12], [P21], [P27], [P1], [P6], [P8], [P23], [P24], [P25], [P4], [P5], [P7], [P14]
Application support	62% (18)	[P2], [P12], [P27], [P28], [P6], [P9], [P13], [P23], [P25], [P26], [P3], [P5], [P7], [P11], [P14], [P16], [P19], [P22]
Interoperability support	17% (5)	[P12], [P27], [P6], [P25], [P29]
Access control	3% (1)	[P6]
Plug and play	0% (0)	-
Peer interface	0% (0)	-
User interface	72% (21)	[P2], [P10], [P12], [P15], [P21], [P27], [P1], [P8], [P9], [P13], [P18], [P24], [P25], [P26], [P29], [P3], [P5], [P11], [P16], [P19], [P22]
Data translation	31% (9)	[P2], [P12], [P7], [P1], [P6], [P25], [P29], [P5], [P16]
Data assurance	0% (0)	-
Security support	21% (6)	[P6], [P16], [P24], [P25], [P4], [P5]

Table I: ISO 23247 FEs and frequency of their implementations in the architectures documented in the selected studies.

without control and actuation FEs are referred to as digital shadows rather than DTs. In contrast to DTs, digital shadows have a one-way data flow between the physical object and its virtual counterpart, allowing the digital object to adapt to the physical object, but not the vice versa [22]. Another interesting observation we made is that most of the current software architectures seem to implement specific patterns of FEs. These are composed of Data collecting, Digital representation, at least one among Simulation, Analytic service or Application support, and at least one of User interface or Reporting. For instance, Pires et al. describe an architecture combining Data collecting, Digital representation, Simulation, and Reporting to support the optimisation of production processes by implementing what-if scenarios [P21]. Han et al. combined Data collecting, Digital representation, Application Support, and Reporting to monitor and trace general parts in continuous casting machines to enable predictive maintenance [P9]. Assad et al. proposed a web-based DT architecture combining Data collecting, Digital representation, Analytic service, Reporting, and User interface [P29].

There are three FEs of the ISO 23247 RA that are not implemented by current DT architectures: Plug and play, Peer interface, and Data assurance. Plug and play support is a FE of the Resource access and interchange sub-entity and is foreseen to enable the dynamic connection of an OME with its digital twin [12]. Peer interface is also a FE of the Resource access and interchange sub-entity (Figure 1) and provides interfaces to other DTs in conjunction with Interoperability support [12]. The lack of implementations for the Plug and play FE may be a consequence of the monolithic nature of current manufacturing processes and assets that may not have the need for frequent and dynamic reconfiguration [23]. Similarly, the lack of Peer interface implementations may suggest the infancy of DT applications and the scarce usage of DT federations. However, we believe that Peer Interface FE will be pivotal in the near future, as remarked by Gartner, which predicted that "*over two-thirds of companies that have implemented IoT will have deployed at least one digital twin in production*" [24]. Data assurance is a FE of the Cross-system entity (Figure 1). As all the entities of cross-system, Data assurance spans across all the entities and sub-entities of a DT. Meaning it ensures data accuracy and integrity both within a DT (i.e., across the entities) as well as among DTs (i.e., when DTs are used in federations). Most of the current DT implementations are based on existing IoT platforms that provide for implicit data management [1]. The lack of explicit Data assurance implementations may be explained with the use of such IoT platforms that suffice the current requirements for data accuracy and integrity. This is especially true for data management within a single DT. On the other hand, data assurance and integrity functionalities among DTs may not be implemented due to the above-mentioned lack of DTs federations. Besides the above three FEs, we found that Access control is implemented in only one study [25]. Section V provides qualitative insights on the implications of such findings.

Highlights RQ1

- ► Current DT architectures tend to implement only a few FEs from the RA according to specific patterns.
- ► Current DT architectures tend to focus on functional aspects and describe digital shadows rather than twins.
- ► Plug and play support, Peer interface, and Data assurance FE are not implemented, while Access control FE is implemented in only one case.

B. *Functionalities not in the ISO 23247 RA (RQ2)*

Several software architectures documented in the studies implement additional functionalities not represented by any FEs of the ISO 23247 RA. Table II summarises such functionalities. The first column contains the name of the component, as found in the majority of the primary studies. The second column provides the percentage and the absolute number of primary studies addressing each component. The third column contains the references to the respective studies. 69% of the selected studies included a functionality dedicated to data storage as part

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Functionality	% (#)	Primary studies
Data storage	69% (20)	[P12], [P15], [P20], [P21], [P16], [P27], [P10], [P4], [P2], [P28], [P1], [P8], [P9], [P23], [P24], [P25], [P29], [P3], [P5], [P14]
Digital twin versioning	6% (2)	[P1], [P27]
Continuous deployment	3% (1)	[P28]

Table II: Functionalities not captured by FEs of the ISO 23247 RA

of their architectures. In the ISO 23247 standard, data storage is only mentioned as a method for exchanging data between Digital twin and User entities: "*the digital twin entity and the user entity can use a database or a cloud to share or exchange the information*" [12]. Hence, no FE explicitly captures such functionality in the RA. By many, data is considered a core ingredient of DTs that allows for the continuous update of virtual replicas during their life-cycles [26]. In this context, the ability to store data is as important as the ability to sense and consume them. For instance, historical data enable most of the descriptive and prescriptive functionalities of DTs [26]. Based on the type of data being stored, we identified three kinds of Data storage components (Table III).

Type of data	Implementation technique	Papers
Raw data	Cloud-based storage	[P12], [P15], [P20], [P21], [P16]
Data processed in real-time	Stream processing platform and NoSQL Database	[P27], [P10], [P4]
Filtered or modeled data	Data models stored in NoSQL database or SQL database	[P2], [P28], [P1], [P8], [P9], [P23], [P24], [P25], [P29], [P3], [P5], [P14]

Table III: Data storage

In the first group, there are components storing massive amounts of raw data coming from IoT gateways using cloud. For instance, in the architecture proposed by Ricondo et al., a statistical approach is employed to generate behavioural models based on the collected data [P15]. In the second group, there are components using data stream processing platforms for enabling real-time data management [P27] [P10] [P4]. Most of the components use Kafka[7]. For instance, Civotta et al. combined Nosql database with Apache Kafka [P4]. The majority of components fall in the third group and collect filtered and modelled data from IoT devices. The pre-processed data is usually stored in Nosql databases. Only a few architectures used relational databases such as MySql and Sql Server for storing structured data [P9], [P23], [P5].

Other functionalities not captured by any FEs of the ISO 23247 RA are DT versioning and Continuous Deployment (CD). Capturing, storing, and integrating different models of DT is considered essential and one of the main challenges for DT systems [27] [P21] [P26] [28]. Indeed, a DT model can evolve over time due to engineering changes to its physical counterpart or changes in modelling interests throughout the physical counterpart's life cycle. The management of different versions of a DT model can be achieved by applying change-based version management principles. In their DT architecture, Lopez et al. include a component for DT version management as a way of efficiently handling different versions of DT models according to their evolution[P27]. They address the need to enable version management for DT models by adopting a data serialization framework called Apache Avro[8]. In their microservice-based architecture, Redeker et al. made use of a dedicated component that allows for continuous deployment of microservices [P28]. The CD functionality consisted of a pipeline based on Gitlab[9], a Container-Registry, and Kubernetes[10] that would perform build and deployment tasks. The pipeline is used to develop, test, and deploy new versions of micro-services to other components of the architecture, such as data infrastructure and business services. Section V provides qualitative insights, e.g., expert opinions, on the implications of such findings.

Highlights RQ2

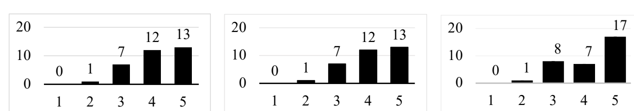
- ► There are three functionalities not captured by the ISO 23247 RA being Data storage, DT versioning, and CD.
- ► Data storage has different implementations depending on the kind of data stored.

V. Evaluation and discussion

In this section, we report and discuss the results of the survey and highlight interesting insights that emerged during the expert interviews. 33 respondents with a background in software architecture and digital twin respond to the survey. 64% of the respondents were academics (professors, assistant professors, etc.), while 36% of the respondents were professionals (software architects, simulation or software engineers, etc.) from multinational companies. We developed the survey following the objectives presented in Section III.

A. FEs not implemented by current DT architectures

One of our objectives was to shed light on the reasons why some FEs of the RA were not implemented by current architectures and their actual need. Hence, we first asked experts to comment on the reasons why some FEs were not implemented, and later we asked them to rate the importance of these FEs and whether these should be implemented into future DT architectures. We used a mix of open- and close-ended questions being linear scale questions ranging from one (not important at all) to five (very important). Figure 3 shows that the majority of the respondents rated the three FEs (not implemented by current architectures) to be important or very important. Experts believe that Plug and play FE could



(a) Plug and play (b) Peer interface (c) Data assurance

Figure 3: Importance of FEs not implemented by current architectures.

add significant value to DTs with respect to the dynamic reconfiguration of the OMEs, rapid design, and maintainability. During one interview, one expert elaborated on the importance of such a FE in relation to the system engineering of DTs:

[7] https://kafka.apache.org/

[8] https://avro.apache.org/

[9] https://gitlab.com/

[10] https://kubernetes.io/

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"for long living systems, there is a need to have a modular architecture that supports systems thinking". Expert opinions on current architecture not implementing this functionality can be grouped into two main categories being maturity of DT and challenges of implementing such a feature. One of the survey respondents remarked that: *"Plug and play is an advanced feature that is built on top of other fundamental features. First, there needs to be agreement on the basics, and then the advanced features can be built."*. During an interview, an expert explained that although DTs are evolving fast, the research still focuses on design-time aspects while *"many run-time details (Plug and play [...] is more evident during operation) will emerge over time"*. Some respondents in the survey pointed at the heavy presence of legacy machines and heterogeneous elements on the shop floor as one of the main obstacles in implementing the Plug and play FE: *"while the dynamic reconfiguration is the key, its realisation might give place to problems (e.g., correctness, trustworthiness)"*. While respondents and experts acknowledge that current support for this functionality is missing due to the reasons mentioned above, they also endorse the importance of the Plug and play FE for DT architectures. In line with this and also considering the increasing demand for flexible production systems [29] and DT federations, we suggest that the DT architectures should provide the Plug and play functionality as suggested by the ISO 23247 RA.

In a similar vein, experts link the lack of support for the Peer interface FE to the maturity of DTs: *"a peer interface with other digital twins is essential to construct a digital twin aggregate"*. While more and more research efforts are focusing on investigating interoperability among different DTs, current DT applications focus on one single DT only and not on an ecosystem of DTs: *"many use cases are focusing on single implementations [...] I expect interfaces between digital twins to come later"*. Respondents identified several challenges hampering the implementation of the Peer interface FE ranging from the diversity of DT models and interface specifications to the lack of semantic interoperability tools and insights into future requirements. Some of the survey respondents, as well as interviewed experts, mentioned the Asset Administration Shell [30] as a possible solution for standardising communication between DTs: *"(in Germany) the Industrial Digital Twin Alliance and the Plattform Industrie 4.0 are specifying a standardised digital representation of assets called the Asset Administration Shell (AAS). AAS addresses exactly this FE."*. When asked about the need for such a FE, respondents and experts agreed that Peer interface is pivotal when targeting scalability of DTs:*"this is [...] needed for smart and flexible production systems, e.g., by means of agent-based communications approaches [...]"*. Besides foreseeing an increasing demand of standardised interfaces, experts also recognise that this would require a global, collaborative effort: *"this is not an issue that any company can solve on its own, but it is a collective effort"*. Hence, we believe that the Peer interface FE will be crucial to future DT applications (not limited to a single supplier).

When it comes to the importance of Data assurance, experts agree that such a FE is essential for DT architectures: *"high information value generally correlates with high data accuracy, integrity, completeness, etc."*. According to the ISO 23247 RA, Data Assurance is responsible for both data accuracy and data integrity. One of the respondents differentiated among the two and considered data accuracy to be part of the data model. During one expert interview, we elaborated more on this and the expert explained that: *"we have different variants of a model depending on their accuracy [...] we need different accuracy depending on different applications"*. Respondent and expert opinions on the reasons behind the lack of implementation of Data assurance by current DT architectures are divided. Some respondents argue that this FE falls outside of the scope of DT architectures: *"digital twin and data capabilities are often developed separately and digital twins reuse existing data infrastructures/architectures"*. Another respondent explains that Data assurance addresses data accuracy and integrity that often depend on external outside factors that are hard to control within the scope of DT architectures:*"accuracy of data depends on sensors measuring the right values [...] data integrity on databases being up-to-date and synchronised"*. Some experts wonder whether data accuracy and integrity should be addressed at the architectural level: *"I do not think it should be solved at the architecture level as it is a question of application-specific implementations"*, and *"it is difficult to express them in models & architectures"*. Considering the respondent and expert opinions on the importance of Data accuracy and reasons for the current lack of implementation by DT architectures, we believe there needs to be a better scoping of the Data assurance FE in the ISO 23247 RA, as well as more information about its relationship to other FEs.

B. Frequency of the implemented FEs

Results from the literature review highlighted that only a few DT architectures implemented FEs of the ISO 23247 RA related to the control and actuation of the OMEs. In the survey, we asked whether this could be interpreted as current architectures proposing digital shadows rather than DTs. We used a dichotomous question (yes or no) sided with an open-ended question for remarks. The majority of the respondents (67%) agreed and some remarked that *"without a bidirectional interaction there is no digital twin"*. Interestingly, one respondent said that it reached a similar conclusion during its research: *"I also investigated a large set of publications on DT. Most of them propose digital shadows [...] digital models that receive some measured data, but that do not give any feedback to the physical counterpart"*. The respondents that disagreed with the above statement argued that: *"there is no single definition of DT in the scientific community. Hence, many colleagues mean simulation when referring to DTs. That is where this divergence comes from."*. Considering this, we believe that the ISO 23347 standard could and should provide unified definitions of the digital model, shadow, and twin. In addition, for each of them, the standard may identify the subset of FEs in the RA that needs to be implemented. Eventually, we believe that architectures for DTs should implement the FEs responsible for the actuation services.

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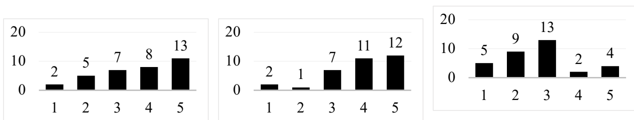
C. Functionalities not captured by FEs in the RA

Another objective was to understand whether the ISO 23247 RA should be extended with additional FEs that were found in the literature and not captured by current FEs (Table II). Hence we asked experts to rate the importance of each additional functionality that we found during the literature review. We used a linear scale question ranging from one (not important at all) to five (very important) sided with an open-ended question for remarks. Figure 4 shows the results of the linear scale question. The majority of the respondents (64%) found



(a) Data storage (b) DT versioning (c) Continuous deployment

Figure 4: Importance of functionality not captured by FEs of the ISO 23247 RA.

the Data storage functionality to be (very) important for DT architectures (Figure 4a). One respondent remarked that: *"data-related aspects are clearly missing [...] and data storage is key to many of the other FEs"*. Another respondent related data storage with existing FEs in the ISO 23247 RA: *"the specifics of data representation, data access, and data archival of digital twins need to be detailed"*. The respondents that did not consider Data storage as important focused on standardised interfaces rather than how the data is stored: *"if the data storage interfaces follow the standard, how exactly data is stored is less important*. We discussed this further during an expert interview. In the expert's view, data storage is mainly a technical issue rather than an architectural concern: *"we just need an interface for data storage; it can be implemented in various ways and does not need a standard in this case"*. Considering the above, we believe that ISO 23247 should have a FE capturing such a functionality. In addition, it may provide recommendations for its implementation based on the type of data being stored, as discussed in Table III.

70% (23/33) of the respondents considered DT versioning (very) important (Figure 4b) hence that the ISO 23247 RA should have a dedicated FE. Reasons for this are related to the possible evolution of DT applications during their life cycles:*"the model of a DT and its services could change, and there is a need to support DT evolution"*. One respondent shared an interesting observation on its relation with Data assurance FE: *"if version numbers are missing, but the model content changes, this change might be undetected leading to corrupted or misinterpreted data"*. During an interview, an expert related DT versioning with the concept of the digital thread, which is a record of a product or system lifetime, from the time of its creation until its end of life [31]. The expert said that *"DT versioning is a must to manage correct information about the digital twin in context of, for example, the digital thread"*. We believe that the ISO 23247 RA should include FEs supporting DT versioning to enable an asset's traceability and provide a holistic view along its entire life cycle.

In contrast to the previous components, the great majority of respondents (81%) rated Continuous deployment as not important (Figure 4c). Continuous deployment is not perceived as an architectural concern but rather as an implementation one: *"CD is a software engineering practice/methodology and not concerned with the quality of a digital twin (architecture)"*. We agree with the respondents and experts and do not recommend the RA to include FE for such a functionality.

D. Importance of being aligned with ISO 23247 RA

In light of the highlighted misalignment with ISO 23247 RA, we asked respondents and experts to determine potential reasons for the misalignment, potential improvements to the standard, and the extent to which current architectures need to restore the misalignment. In addition, we asked respondents to rate the importance of aligning DT architectures with ISO 23247 RA. According to the majority of respondents (61%), aligning DT architectures with the ISO 23247 RA is (very) important (Figure 5). Respondents and experts pointed at the

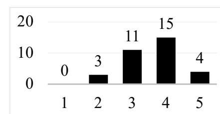


Figure 5: Importance of being aligned with the ISO 23247 RA

maturity of DTs and awareness of the standard as two main reasons for the identified misalignment. (The misalignment) *"may reveal that the ISO 23247 RA may have gone further compared to the current DT maturity stage"*. Further, *"it may reveal the need to increase the standard diffusion and to create incentives for its adoption in testing and documenting DTs in industrial practice."* Respondents and experts agreed that a collaborative effort is required to improve the alignment: *"ISO is interested in improving the standard, and DTs urgently need standards to evolve. Both need to make an extra effort"*. Having DT architectures aligned with the RA of the ISO 23247 can provide a common terminology that enables *"to understand, compare and integrate different solutions developed by different departments, organisations, and suppliers, for the purpose of implementing a working solution"*. In turn, a common terminology would improve interoperability, *"otherwise each organisation makes its own solution and definition, that makes interoperability very difficult!"*. However, some respondents and experts had doubts about the current recommendation of the standard about the implementation of all the FEs: *"standards are absolutely essential to guide the industry [...] the industry should try to adhere to ISO 23247 [...] but, in my opinion, not all FEs are essential in all situations"* to *"fulfill the business goals"*.

VI. Related Work

Aligning software architectures with, e.g., business goals [32], existing standards, is pivotal, and even mandatory, in several domains, such as automotive and other safety-critical ones. This need has been recently discussed in a work by Shahrokni et al. focusing on the importance of compliance with safety and security standards, e.g., ASPICE, in the automotive domain [33]. While there are some research works focusing on checking the alignment of software architectures with existing standards in different domains, to the best of our

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knowledge, this work represents the first research focusing on assessing the alignment of current DT software architectures in manufacturing with the ISO 23247 RA. Hence, the remainder of this section brings the reader's attention to similar works, possibly in other domains.

Badawi et al. investigated how to regulate the interoperability between systems using the ISO/IEEE 11073 Personal Health Device (X73-PHD) standard. To this end, they reviewed the compliance of existing healthcare information systems with the standard [34]. Eventually, they highlighted some challenges in deploying systems based on the standard and how current research addresses the elicited challenges. For instance, they argued that the standard does not address security-related challenges such as authentication and authorization. The work by Badawi et al. uses a systematic process to extract and analyse the data. In our work, we complement the results from the literature review with a survey and expert interviews.

The ISO 11783 standard, also referred to as ISOBUS, is the de-facto standard for machinery communication within the agriculture domain. Paraforos et al. conducted a literature review on control systems and sensors compatible with ISOBUS [35]. From an operation-based perspective, they identified three primary ISOBUS-related research works: (i) guidance and control, (ii) data acquisition and transfer, and (iii) data management and analytics. In addition, they identified future challenges and limitations related to ISOBUS. The main difference with our work is that they focus on identifying physical systems (sensors and control systems) in the agriculture domain, while our research focuses on software architectures.

Sandgren and Antinyan provided a software safety analysis method to help practitioners to comply with safety standards in agile software development [36]. The work focuses on the automotive domain and uses the ISO 26262 standard. Practitioners were used for iterating across the action research cycles that brought to the definition of the method. The method was then applied to develop an Electronic Control Unit (ECU) at Volvo. Another work on the same standard is reported by Henriksson et al. with suggestions on how to improve the standard to cover machine learning capabilities [37]. There is a similar motivation behind our work as we aim to raise awareness of the alignment between industry, academic research, and the ISO 23247 standard and influence their evolution. However, in our research, we leveraged a holistic methodology being a mix-methods approach.

VII. Conclusion and Future Work

In our experience working in the field, we found that several multinational companies started to use the ISO 23247 reference architecture, although its adoption is still in its embryonic stages. Then, we are far from being able to properly measure the compliance of existing digital twin architectures in manufacturing with the reference architecture proposed in the standard. To shed some light on the alignment of current systems with the ISO 23247 reference architecture, we analysed 29 digital twin architectures in manufacturing resulting from a systematic literature review of 140 peer-reviewed studies against the ISO 23247 reference architecture. In addition, we performed a survey with 33 respondents and conducted four semi-structured, in-depth expert interviews. Eventually, we reported on the existing misalignment between current digital twin architectures and the ISO 23247 reference architecture. One may argue that the misalignment of current architectures was expected given the recent publication date of the standard. However, we further elaborate on the specific FE that were not aligned, investigate the reasons of such misalignment and to which extent the existing misalignment need to be restored.

We found out that current architectures mostly focus on functional aspects, neglecting non-functional entities related to, e.g., security and maintainability. None of the analysed architectures implements Plug and play support, Peer interface, and Data assurance, while Access control is implemented in only one case. Reasons for such a lack of implementation are the maturity of current digital twin applications and implementation challenges. It is worth noting that currently ISO 23247 recommends that all FE need to be implemented, while from our investigation current architectures tend to implement a subset of FEs according to specific patterns. In this regard, a potential improvement of the standard can be differentiating mandatory FEs from optional ones that add additional functionalities. We also found that the ISO 23247 reference architecture misses support for two functionalities implemented by current architectures being: Data storage and Digital twin versioning. Both survey respondents and experts during the interviews agreed that architectures should be aligned with the ISO 23247 reference architecture and that this should be extended with functional entities supporting data storage and digital twin versioning. In fact, being aligned to the ISO 23247 reference architecture is perceived as pivotal for tackling challenges, such as interoperability and evolvability, that no single organisation can solve on its own without a joint and collective effort. In this respect, ISO 23247 is also expected to provide a context where different solutions can be compared and analysed using, e.g., standard terminology. Considering the return on investment of using and aligning to reference architectures [5], respondents and experts consider the effort of aligning with the ISO 23247 reference architecture worth. However, they remarked on the need for the reference architecture to keep evolving. On the one hand, current functional entities should be better explained with implementation details and relations among them. On the other hand, new functionalities, as in the case of data storage and digital twin versioning, should be considered.

Future work may encompass several directions. One direction is to build on the results of this study and propose a refined reference architecture for digital twins in manufacturing. Considering the importance of interoperability for digital twins, another direction is to build on the results of this study and assess how interoperability among architecture components implementing functional entities of the ISO 23247 standard is realised using the interoperability model by Wang et al. [38].

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