Review and Classification of Digital Manufacturing Reference Architectures

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Abstract For the next generation of production systems, companies require new architectures for designing highly connected systems to increase the efficiency and capabilities of their value chains. Reference architectures help to effectively derive systems architectures. Over the last decades, numerous reference architectures for digital manufacturing have been proposed. This paper presents a framework to classify reference architectures based on five main themes identified in the literature. It will identify gaps in existing reference architectures based on an analysis of the proposed framework and comparison to other classification approaches.

Key words: Industry 4.0, Reference Architecture, Digital Manufacturing, Internet of Things (IoT), Cyber-Physical Systems (CPS)

1 Introduction

The application of digital technologies to industrial processes has led to a paradigm shift in the manufacturing industry. For the next generation of production systems, companies utilise the constant information flow of highly connected systems in order to increase the efficiency of processes, improve the product design, and enhance the capabilities of logistics and maintenance applications [1]. There is a need for new system architectures to create and support these interconnected systems [2].

Reference architectures guide the design of system architectures. Over the years, numerous reference architectures under different notions of digital manufacturing have been proposed [1, 3, 4, 5, 6]. However, some aspects of digital manufacturing are underrepresented so far. The aim of this paper is to review and classify digital manufacturing reference architectures in order to clarify the applicability and necessity of these reference model to specific areas in digital manufacturing. We begin by clarifying some of the key terms.

Digital Manufacturing *Digital manufacturing* defines '*the application of digital information [from multiple sources, formats, owners] for the enhancement of manufacturing processes, supply chains, products and services*' [7]. It covers a broad area of themes including Industry 4.0 [8] and Smart Manufacturing [9, 10, 11], Internet

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of Things (IoT) [12] and Industrial Internet of Things (IIoT) [13], Cyber-Physical Systems (CPS) [14, 15] and manufacturing control systems [1, 16]. In this paper we specifically focus on reference architectures which refer to these terms.

Reference Architectures To address the cost of customised modelling and implementing digital solutions, Karsai et al. [17] proposed a metamodelling approach, which establishes a second level of modelling. This meta-level contains information about the structure of the underlying model. In the context of digital manufacturing, reference architectures follow the idea of meta models. *Reference architectures (or meta models) guide the design of system architectures by providing a structured template solution with common terminology* [18]. While the system architecture conceptualises the digital manufacturing system by providing a virtual description of its assets, reference architectures can be abstracted as well. The meta-meta-level includes core abstractions of reference architectures in terms of their organisation and ontology [17, 19]. The four-layer metamodelling structure is presented in Figure 1.

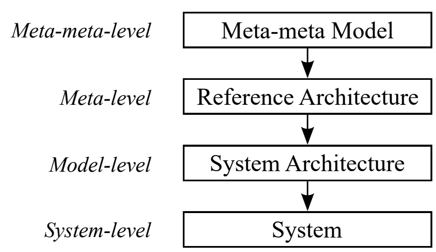

Fig. 1 The four-layer metamodelling approach for digital manufacturing [17]

We further specify that digital manufacturing reference architectures are characterised by dimensions, components or some form of structure [6] in combination with a certain longevity, whereby related key publications and standards are referenced since their release. Reference architectures do not constitute principles, generic design guidelines, conceptual frameworks or standards and technologies, such as services [20] and agents [21], which are used to develop system architectures and implement concrete systems. However, technologies can represent a key feature of a reference architecture.

The paper is structured as follows. In Section 2, we provide an overview of reference architectures for digital manufacturing and describe current classification approaches in the literature. While Section 3 introduces the proposed classification approach and analyses the different classes, Section 4 covers gaps in digital manufacturing reference architectures. The paper concludes by indicating potential future research opportunities.

2 Background

This section develops some of the key background for this paper. It gives an overview of reference architectures related to digital manufacturing. We also review current classification approaches of meta models presented in the literature.

2.1 Digital Manufacturing Reference Architectures

Over the last decades, various reference architectures have been proposed in the literature. In this review, we have selected reference architectures relevant to digital manufacturing based on two criteria: (1) the meta model addresses a main theme related to digital manufacturing, and (2) the proposed architecture meets the previously defined characteristics of a reference architecture. The selected reference architectures for digital manufacturing are presented in Table 1.

Table 1 Selected Digital Manufacturing Reference Architectures

Digital Manufacturing Reference Architecture	Publication
5C	[22]
8C	[23]
Activity Resource Type Instance Architecture (ARTI) [a]	[24]
ADACOR^2	[25]
Adaptive Holonic Control Architecture (ADACOR)	[26]
Aligned Reference Architecture for Digital Factories	[27]
Alliance for Internet of Things Innovation (AIOTI) High Level Architecture (HLA)	[28]
Big Picture	[29]
Blockchain enabled CPS Architecture (BCPS)	[30]
Cisco IoT	[31]
Computer Integrated Manufacturing Open System Architecture (CIMOSA)	[32]
Computer-Aided Manufacturing - International (CAM-I)	[16]
CPS Shop Floor Architecture	[33]
Cyber-Physical Architecture of Internet of Things	[34]
Cyber-Physical Production Systems (CPPS)	[14]
Delegate Multi-Agent System (D-MAS)	[35]
Digital Twin as a Service (DTaaS) Architecture Reference Model	[36]
Dynamic Architecture for an Optimised and Reactive Control of Flexible Manufacturing Scheduling (ORCA-FMS)	[37]
Embedded Agent CPS Architecture	[38]
GRAI Integrated Method (GIM)	[39]
Graphs with Results and Actions Interrelated (GRAI)	[40]
High Level Architecture for the Factory Of the Future	[41]
Holonic Component-Based Architecture (HCBA)	[42]
Holonic Hybrid Control Model (H^{2}CM)	[43]
IBM Industry 4.0	[44]
Industrial Internet Consortium (IIC) Industrial Internet Reference Architecture (IIRA)	[18]
Industrial Internet Integrated Reference Model (I3RM)	[45]
Industrial Value Chain Reference Architecture (IVRA)	[46]
Integrated Computer-Aided Manufacturing (ICAM)	[16]
Integrated Manufacturing Planning and Control System (IMPACS)	[16]
Integration of Informatisation and Industrialisation (iI&I)	[10]
Intelligent Manufacturing System Architecture (IMSA)	[47]
International Telecommunication Union IoT (ITU-IoT)	[48]
Internet of Things Reference Architecture (IoT RA)	[49]
IoT Architectural Reference Model (IoT-ARM) [a]	[50]
ISO-IEC Joint Working Group (JWG21) [a]	[4]
Knowledge-based Real Time Supervision in CIM (ESPRIT Project 932)	[16]

KSTEP	[4]
Manufacturing Blockchain of Things (MBCoT) Architecture	[51]
Manufacturing Management and Control System (MMCS)	[52]
National Bureau of Standards (NBS)	[16]
National Institute of Standards and Technology (NIST) Smart Manufacturing Ecosystem (SME)	[53]
NIST Framework for Cyber-Physical Systems	[54]
NIST Service-Oriented Smart Manufacturing Architecture	[55]
POLLUX	[56]
PROCOS Generic CIM Architecture	[52]
Product, Resource, Order and Simulation Isoarchic Structure (PROSIS)	[57]
Product Resource Order Staff Architecture (PROSA) [a]	[58]
Purdue Enterprise Reference Architecture (PERA) [a]	[59, 60]
Reference Architecture Model Edge Computing (RAMEC)	[61]
Reference Architecture Model Industry 4.0 (RAMI 4.0)	[62]
Reference Model for Smart Factories	[6]
Scandinavian Smart Industry Framework (SSIF)	[4]
Service-oriented Holonic Manufacturing System (SoHMS)	[63]
Smart Manufacturing Standards Landscape (SM2)	[64]
Stair-like CIM System Architecture (SLA)	[65]
Stuttgart IT Architecture for Manufacturing (SITAM)	[66]
'Surveillance Active Ferroviaire' (SURFER)	[67]
Vertical Integration Architecture	[68]
World Wide Web Consortium (W3C) Web of Things (WoT)	[69]
WSO2 IoT	[70]

[a] Meta-meta model

The first attempts towards a reference model for digital manufacturing were made under the notion of Computer Integrated Manufacturing (CIM). CIM aims to integrate the complete manufacturing enterprise by using interoperable systems in conjunction with novel management concepts to increase efficiency [71]. While the majority of proposed reference architectures, including ICAM, CAM-I and GRAI, merely address specific aspects of CIM, there are two main approaches which aim to achieve a global enterprise integration [16]: the Computer Integrated Manufacturing Open System Architecture (CIMOSA) [32] and the Purdue Enterprise Reference Architecture (PERA) [59]. CIMOSA consists of an event-driven framework which describes the complete life cycle of the integrated enterprise by using four views (Function, Information, Resource, and Organisation). PERA integrates enterprise and control systems by modelling business and production processes as well as parts of the information and control system hierarchically. Since it defines a core element of IEC 62264 (ANSI/ISA-95) [60], which forms the basis for numerous successors, we also view PERA as a meta-meta model.

While PERA aims to achieve a vertical integration, two major paradigms, namely Industry 4.0 and Smart Manufacturing, propose a horizontal integration of manufacturing and enterprise systems through the creation of decentralised networks of connected information systems, which induce flexibility and increase efficiency across the value chain [9, 11]. Various reference architectures have been presented based on the concept of Industry 4.0, an initiative by the German government, which aims to transform manufacturing via digitalisation and new technologies [8]. As the official reference model for Industry 4.0, the Reference Architecture Model Industry 4.0 (RAMI 4.0) [62] provides a common understanding of standards for the design of components, which enables their specification as well as life cycle, including their technical and organisational functions. In the United States, the term Smart Manufacturing has prevailed, which intensifies the application of networked information-based technologies to manufacturing and supply chain processes [9, 11]. The National Institute of Standards and Technology (NIST) proposes the Smart Manufacturing Ecosystem (SME) [53], which provides a standards landscape for smart manufacturing systems. This three-dimensional reference model describes product, production and business dimensions with their corresponding life cycles. While IEC 62264 forms the basis for the vertical integration of enterprise functions for RAMI 4.0 and NIST SME, both frameworks support the horizontal integration of systems according to the concepts of Industry 4.0 and Smart Manufacturing.

An approach to create networks of connected information systems for manufacturing describes the use of Cyber-Physical Systems (CPS). CPS are collaborating computational units which are connected to the surrounding physical world and its processes [14]. The 5C reference architecture [22] guides the development of networked CPS for manufacturing processes of Industry 4.0. Its hierarchical structure consists of five levels that describe the attributes of these systems from the connection level to the cognition level. NIST proposes an abstract Framework for Cyber-Physical Systems [54] which identifies cross-cutting concerns (Societal, Business, Technical) and addresses relevant aspects by using artifacts for the conceptualisation, realisation, and assurance of CPS.

In addition to CPS, the concept of the Internet of Things (IoT) has been introduced to integrate technologies and communication systems. The IoT enables collaboration among its components by communicating through a unique addressing scheme in order to achieve a common goal [12]. For a better understanding of manufacturing processes, the Industrial Internet of Things (IIoT) includes the areas machine to machine (M2M) and industrial communication technologies for automation applications [13]. Besides general IoT reference architectures, such as ITU-IoT [48] and IoT-ARM [50], several reference model have been proposed that specifically cover the manufacturing domain, most notably the Industrial Internet Reference Architecture (IIRA) presented by the Industrial Internet Consortium (IIC) [18]. As a standard-based open architecture for industrial internet applications, IIRA provides a set of viewpoints (Business, Usage, Functional and Implementation) to support the design of IIoT systems.

In order to cope with rapid changes in the manufacturing environment, the holonic paradigm was proposed in the 1990-2010s, which considers the manufacturing system to consist of autonomous entities collaborating to achieve a common goal [1, 42]. Besides PROSA [58], which serves as a template for subsequent models, two major reference architectures have been suggested: the Holonic Component-Based Architecture (HCBA) [42] and the Adaptive Holonic Control Architecture (ADACOR) [26]. The decentralised architecture of HCBA is composed of autonomous, modular, cooperative and intelligent building blocks, which are able to cope with rapid changes, yielding a reconfigurable production systems. ADACOR employs a supervising entity to balance dynamically between a centralised and decentralised structure, which optimises the production system and leads to fast reactions to unexpected disturbances.

In the last 25 years, various new technologies have been introduced to support the development of digital manufacturing systems, such as Multi-Agent Systems

(MAS) [21], digital twins [72] and blockchain [73]. Above all, services as part of a Service-Oriented Architecture (SOA) [20] characterise a loosely coupled, standard-based and protocol-independent form of distributed computing in order to integrate information systems with business processes. Besides leveraging them for manufacturing processes, approaches have been made to incorporate these technologies in reference architectures. Services define the core technology for the majority of reference models, such as IBM Industry 4.0 [44] and the NIST Service-Oriented Smart Manufacturing Architecture [55].

2.2 Classification Approaches

Several attempts have been made in the literature to classify digital manufacturing reference architectures: Monostori [14] links Cyper-Physical Production Systems (CPPS) to previous developments in digital manufacturing, such as holonic manufacturing and digital factories. Whereas Weyrich and Ebert [74] consider RAMI 4.0 and IIRA to be part of the same class of IoT reference models, Kassner et al. [66] distinguish between abstract frameworks for Industry 4.0 and Smart Manufacturing, cross-domain-spanning reference architectures and concrete manufacturing IT architectures. Li et al. [10] identify reference models for Smart Manufacturing, coinciding with the class presented by Soares et al. [6], which contains reference architectures for the entire ecosystem of a factory. In contrast to other classifications of IIoT related models, Bader et al. [3] systematically select reference architectures based on the number of searches done via internet search engines.

While there are various approaches to compare and align different meta models for digital manufacturing [2, 4, 15, 45, 28], a well-defined, direct classification of selected frameworks has not been provided. Moreover, there are no comprehensive reviews of reference architectures which cover all areas relating to digital manufacturing. Although some reviews are supported by mappings, they do not investigate reference models across multiple digital manufacturing domains, such as IoT, CPS and holonic manufacturing systems.

In this paper we provide a comprehensive review and classification of digital manufacturing reference architectures and address research gaps. This contribution can also help to identify relevant reference architectures for the manufacturing industry.

3 A Classification Approach for Digital Manufacturing Reference Architectures

This section outlines the classification approach for digital manufacturing reference architectures. After an overview and a detailed description of the different classes, we provide an analysis and compare our approach to the classifications carried out in the literature.

3.1 Classes

Based on the digital manufacturing themes identified in the literature, the proposed framework for classifying digital manufacturing reference architectures consists of five classes:

(A) Smart Manufacturing Reference Architectures,
(B) Internet of Things Reference Architectures for Manufacturing,
(C) Reference Architectures for Manufacturing Control,
(D) Cyber-Physical Sytems Reference Architectures for Manufacturing, and
(E) General Internet of Things Reference Architectures.

Class A is further differentiated into *standard-based* and *technology-based* frameworks. Similarly, Class D separates *technology-based* frameworks from *abstract* CPS reference models. Finally, we subdivide manufacturing control architectures into *CIM frameworks* and *distributed autonomous control architectures*. An overview of the classes is presented in Figure 2. The main aim of this classification framework is to provide guidance for the applicability of reference architectures to specific areas in digital manufacturing.

A - Smart Manufacturing Reference Architectures The reference architectures of this class provide a structure for the design of components and systems for smart manufacturing, Industry 4.0 and smart factories. These meta models describe standards frameworks or propose technology architectures to achieve a horizontal integration of manufacturing and enterprise systems.

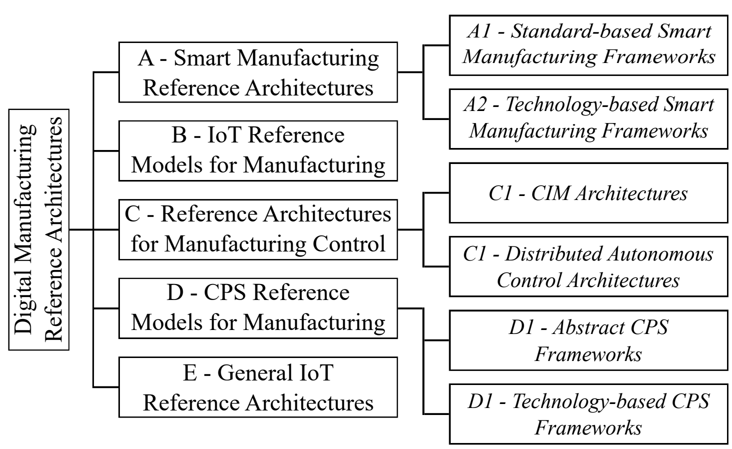

Fig. 2 Classification framework for digital manufacturing reference architectures

A1 - Standard-based Smart Manufacturing Frameworks This subclass contains reference architectures that are composed of a set of views, dimensions and life cycle models as well as a standards framework for Smart Manufacturing. Most notably, RAMI 4.0 and NIST SME characterise reference architectures which provide a set of standards and model the entire life cycle of relevant enterprise processes. Several successors share similarities with those models. While the Intelligent Manufacturing System Architecture (IMSA) [47], the Industrial Value Chain Reference Architecture (IVRA) [46], the Smart Manufacturing Standards Landscape (SM2) [64] and KSTEP [4] resemble features of RAMI 4.0, the Big Picture of standards [29] and the Scandinavian Smart Industry Framework (SSIF) [4] are comparable to NIST SME [3, 4, 5]. New meta models have been developed by analysing existing reference architectures. Soares et al. [6, 27] and ISO-IEC Joint Working Group (JWG21) [4] propose models based on the main dimensions and views of digital factories as well as Smart Manufacturing, whereas the Integration of Informatisation and Industrialisation (iI&I) [10] reference model describes the interaction of new technologies with enterprise functions. The Reference Architecture Model Edge Computing (RAMEC) [61] concentrates on industrial automation and provides a meta model for the design of components based on the Edge Computing paradigm.

A2 - Technology-based Smart Manufacturing Frameworks In contrast to the abstract, standard-based Smart Manufacturing frameworks, the reference architectures of this subclass are based on technologies, thus being more concrete. The majority of reference models leverage services for achieving the goals of Smart Manufacturing and Industry 4.0, including IBM Industry 4.0 [44], the NIST Service-oriented Smart Manufacturing Architecture [55], the Stuttgart IT Architecture for Manufacturing (SITAM) [66], and the Digital Twin as a Service (DTaaS) Architecture Reference Model [36]. While the last utilises digital twins as well, only few approaches rely on technologies other than services, such as the Manufacturing Blockchain of Things (MBCoT) [51], which combines blockchain with the IIoT to configure traceable and decentralised intelligent manufacturing systems.

B - Internet of Things Reference Models for Manufacturing The reference architectures of this class guide the creation of IoT and IIoT components, which specifically cover manufacturing applications. These meta models are structured and consists of a set of architectural views. Besides RAMI 4.0 and NIST SME, IIRA defines a vita meta model for the IIoT. Compared to IIRA, the Internet of Things Reference Architecture (IoT RA) [49] and the Industrial Internet Integrated Reference Model (I3RM) [45] describe similar cross-cutting functions and views [5], whereas the latter includes features of RAMI 4.0 and NIST SME as well. Further, the High Level Architecture (HLA) [28] proposed by the Alliance for Internet of Things Innovations (AIOTI) augments IoT-ARM by introducing three fucntional layers (Application, IoT and Network), which covers different IoT use cases, including manufacturing. While the above reference architectures are more abstract, the Web of Things (WoT) [69] introduced by the World Wide Web Consortium (W3C) aims to create interoperable systems for various IoT applications. Its architecture consists of modular building blocks, which can be applied to three levels (Device, Gateway and Cloud), and standardised, protocol-independent interfaces.

C - Reference Architectures for Manufacturing Control This class contains reference models which support the design of systems for manufacturing control. These meta models describe the integration of enterprise and control systems or propose distributed autonomous control architectures.

C1 - Computer Integrated Manufacturing Architectures The reference models of this subclass are based on the concepts of computer integrated manufacturing. Although many CIM reference architectures have been proposed over the years, including ICAM, CAM-I, NBS, the ESPRIT Project 932 and IMPACS [16], GRAI [40] and GIM [39], as well as PROCOS and MMCS [52], only PERA and CIMOSA have prevailed. Since they aspire a global enterprise integration, PERA and CIMOSA form the basis for the vertical integration of several Smart Manufacturing frameworks, including RAMI 4.0 and NIST SME. More recently, the Stair-like CIM Architecture (SLA) [65] converges towards Smart Manufacturing frameworks by providing a meta model, which describes subsystems, the stepwise realisation of systems as well as corresponding architectural views and life cycle models.

C2 - Distributed Autonomous Control Architectures This subclass contains reference architectures for the distributed autonomous control of manufacturing systems. Most notably, these meta models have been proposed under the notion of holonic manufacturing. PROSA [58] has been used as a meta-meta model to create PROSIS [57], which simulates the evolution of the manufacturing system, the Holonic Hybrid Control Model (H^2CM) [43] for monitoring flexible control systems, and ARTI [24], which further generalises PROSA. Besides HCBA and ADACOR as major reference architectures for distributed autonomous manufacturing control, Delegate Multi-Agent Systems (D-MAS) [35] and Service-oriented Holonic Manufacturing Systems (SoHMS) [63] combine holonic components with technologies. 'Surveillance Active Ferroviaire' (SURFER) [67], the Dynamic Architecture for an Optimised and Reactive Control of Flexible Manufacturing Scheduling (ORCA-FMS) [37], $ADACOR^2$ [25] and POLLUX [56] propose dynamic control architectures.

D - Cyber-Physical Systems Reference Models for Manufacturing The meta models of this class guide the development of CPS for Smart Manufacturing and Industry 4.0 applications. While some of these reference architectures provide a structure, such as layers or hierarchy levels, the primary focus lies on creating component-based systems.

D1 - Abstract Cyber-Physical Systems Frameworks Based on the concepts of CPS, the reference architectures of this subclass provide abstract design structures. There are two groups of abstract CPS frameworks. First, the 5C architecture, the 8C model [23] and the CPS Shop Floor Architecture [33] provide a guide for the development of CPS as components for Smart Manufacturing and Industry 4.0. The second group of reference architectures, which includes Cyber-Physical Production Systems (CPPS) [14], the Vertical Integration Architecture by Pérez et al. [68], the

NIST Framework for Cyber-Physical Systems and Cyber-Physical Architecture of Internet of Things [34], proposes structures for designing the Smart Manufacturing application as a whole similar to standard-based Smart Manufacturing frameworks.

D2 - Technology-based Cyber-Physical Systems Frameworks In this subclass, technologies characterise the foundation of the reference architectures for manufacturing applications. Similar to the technology-based Smart Manufacturing frameworks, these CPS meta models are more concrete compared to the previous subclass. While Nascimento et al. [38] and Havard et al. [41] rely on agents, Lee et al. [30] utilise blockchain for the development of CPPS.

E - General Internet of Things Reference Architectures The reference models of this class provide a structure for the design of IoT components. While these can be used for creating manufacturing systems as well, these reference architectures focus on general IoT applications. The IoT architecture by the International Telecommunication Union (ITU-IoT), the Cisco IoT model [31] as well as the WSO2 IoT architecture [70] utilise layers to represent the communication between application and network, whereas the IoT Architectural Reference Model (IoT-ARM) consists of views for the structural aspects of the IoT, and perspectives to ensure that the derived system meets its requirements.

In the following we analyse the proposed classification approach by highlighting relevant differences between the classes and emphasise reference architectures, that were difficult to classify. Finally, we compare our framework to alternative classification approaches in the literature.

3.2 Analysis of the Classification Approach

Numerous reference architectures have been proposed over the last years. However, the reference models vary significantly in terms of their digital manufacturing theme and level of abstraction. To address these issues we have proposed a framework which provides a comprehensive approach for classifying digital manufacturing reference architectures. It differentiates between five digital manufacturing themes and separates abstract and standard-based meta models from technology-based reference architectures, and distinguishes between CIM and distributed autonomous control architectures.

Based on an extensive literature review, we have identified and classified 61 reference architectures for digital manufacturing, which is presented in Table 2. While every meta model refers to at least one of the five classes, some reference architectures can be assigned to multiple classes. In particular, abstract meta models, which can be found in *A1*, B and *D1*, are more difficult to classify than technology-based reference architectures, since they describe characteristics of multiple classes. For example, both RAMI 4.0 and IIRA can be viewed as Smart Manufacturing or IoT reference models for manufacturing, which correlates with other classification approaches in the literature [6, 10, 74, 66]. Further, meta models based on the holonic paradigm in subclass *C2* constitute altering levels of abstraction, thus impeding the classification procedure. Whereas HCBA and D-MAS specify agent-oriented reference architectures, which characterise technology-based approaches, PROSA defines an abstract meta-meta model.

Table 2 Classified Digital Manufacturing Reference Architectures

Class	Features	Relevant Reference Architectures
A1 - Standard-based Smart Manufacturing Frameworks	The meta models are composed of a set of views, dimensions, and life cycle models as well as a standards framework for Smart Manufacturing	Aligned Reference Architecture for Digital Factories [27], Big Picture [29], IVRA [46], iI&I [10], IMSA [47], JWG21 [4], KSTEP [4], NIST SME [53], RAMEC [61], RAMI 4.0 [62], Reference Model for Smart Factories [6], SSIF [4], SM2 [64]
A2 - Technology-based Smart Manufacturing Frameworks	Technologies (Services, agents, etc.) form the basis of these reference architectures for Smart Manufacturing	DTaaS Architecture Reference Model [36], IBM Industry 4.0 [44], MBCoT Architecture [51], NIST Service-Oriented Smart Manufacturing Architecture [55], SITAM [66]
B - IoT Reference Models for Manufacturing	The structured meta models for the design of IoT and IIoT components consists of a set of architectural views	AIOTI HLA [28], IIC IIRA [18], I3RM [45], IoT RA [49], W3C WoT [69]
C1 - CIM Architectures	The reference models are based on the concept of CIM	CIMOSA [32], CAM-I [16], GIM [39], GRAI [40], ICAM [16], IMPACS [16], ESPRIT Project 932 [16], MMCS [52], NBS [16], PROCOS [52], PERA [59, 60], SLA [65]
C2 - Distributed Autonomous Control Architectures	The meta models design distributed autonomous manufacturing control systems	ARTI [24], $ADACOR^2$ [25], ADACOR [26], D-MAS [35], ORCA-FMS [37], HCBA [42], H^2CM [43], POLLUX [56], PROSIS [57], PROSA [58], SoHMS [63], SURFER [67]
D1 - Abstract CPS Frameworks	The reference architectures provide an abstract framework for the structured design of Smart Manufacturing systems based on CPS	5C [22], 8C [23], CPS Shop Floor Architecture [33], Cyber-Physical Architecture of Internet of Things [34], CPPS [14], NIST Framework for CPS [54], Vertical Integration Architecture [68]
D2 - Technology-based CPS Frameworks	Technologies (Services, agents, etc.) form the basis of these reference architectures for the design of Smart Manufacturing systems based on CPS	BCPS [30], Embedded Agent CPS Architecture [38], High Level Architecture for the Factory Of the Future [41]
E - General IoT Reference Architectures	The reference models consist of a structure for the design of general IoT application, which can also be used to create manufacturing systems	Cisco IoT [31], ITU-IoT [48], IoT-ARM [50], WSO2 IoT [70]

Compared to other classification approaches [6, 10, 14, 74], we propose a framework for a precise classification of digital manufacturing reference architectures, which can be utilised for future meta models as well. In contrast to Bader et al. [3], we suggest to differentiate by major digital manufacturing themes instead of referring to only broadly known reference models. Similar to Kassner et al. [66], we separate between abstract and concrete reference architectures to enable a clear delimitation and simplify the classification process.

4 Gaps in Digital Manufacturing Reference Architectures

The applicability of reference architectures for digital manufacturing is subject to several limitations. Abstract and standard-based reference models cover more aspects of the manufacturing application but complicate the design of systems. For instance, NIST SME and IIRA consist of standards, viewpoints and life cycle models that characterise the Smart Manufacturing or IIoT system, but hardly provide specific implementation guidelines. Besides, these reference architectures describe various levels of maturity. While RAMI 4.0 and Big Picture are already standardised, KSTEP and iI&I merely outline abstract frameworks.

Although reference architectures are able to model Smart Manufacturing and Industry 4.0 applications as a whole or focus on specific aspects of digital manufacturing, there are several issues that have not been addressed thus far. None of the reviewed reference models consider different sizes of operational processes of small and medium-sized enterprises (SMEs) and larger manufacturers. It is important to separate SMEs from larger companies, because they struggle to adopt Smart Manufacturing and related concepts due to a lack of knowledge, skills and resources [75], thus requiring a different approach. Moreover, these meta models do not address the cost implications of designing and deploying systems, which embodies a major obstacle of the digitalisation efforts made by SMEs [76]. While some initiatives, such as the ISO-IEC Joint Working Group (JWG21), focus on the gaps among international standards, there is no reference architecture that covers all aspects of digital manufacturing. Finally, comparisons and alignments have only been made for only a few selected reference architectures [2, 4, 15, 45, 28]. Therefore, there is a need for mapping meta models within and across the classes presented in this paper in order to analyse the necessity of existing approaches in detail.

5 Conclusions

In this paper we have reviewed and classified various reference architectures based on five digital manufacturing themes. An analysis and comparison with other approaches in the literature has shown that the proposed framework provides a more comprehensive and precise classification, which can be used for future reference architectures as well. The aim of this paper was to analyse the practicality and need for digital manufacturing reference architectures. While separating concrete, technology-based approaches from abstract meta models clarifies the applicability of reference models to specific areas in digital manufacturing, the classification helps to identify relevant meta models and those which show similarities.

Digital manufacturing reference architectures vary significantly in terms of their theme and level of abstraction. While every meta model refers to at least one of the five classes, abstract reference architectures manifest features of multiple classes, which complicates their classification. Moreover, altering levels of abstraction can be observed for holonic manufacturing architectures. Since these meta models do not consider the digital manufacturing application as a whole but merely focus on specific aspects, differentiating between abstract meta models and technology-based approaches is more challenging. There are three main directions that can help to increase the applicability of digital manufacturing reference architectures. First, none of the reviewed reference models address different sizes of operational processes and the cost of developing systems thus far. Second, there is no meta model that covers all aspects of digital manufacturing, which would reduce the need for introducing new reference architectures. Finally, to study the necessity of existing approaches in detail, there is a need for mapping meta models within and across the classes presented in this paper.

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