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A review of reference architectures for digital manufacturing: Classification, applicability and open issues

Jan Kaiser [a,*], Duncan McFarlane [a], Gregory Hawkridge [a], Pascal André [b], Paulo Leitão [c]

[a] University of Cambridge, Institute for Manufacturing, 17 Charles Babbage Rd, Cambridge CB3 0FS, United Kingdom
[b] University of Nantes, Laboratory of Digital Sciences of Nantes, 2 Chemin de la Houssinière, 44322 Nantes, France
[c] Polytechnic Institute of Bragança, Research Center in Digitalization and Intelligent Robotics (CeDRI), 5300-253 Bragança, Portugal

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ABSTRACT

The industrial application of digital technologies in manufacturing can result in an increased efficiency of processes and an opportunity to integrate production, logistics and maintenance functions. However, increasingly interconnected manufacturing information means progressively more complex systems. Therefore, there is an ever growing need to provide structure in the design and development of such information systems which is the role of a system architecture. So called ‘reference architectures’ guide the design of system architectures used in particular applications. Reference architectures are models of information functions and their connections that provide a structured template with common terminology. Over the last decades, various reference architectures relevant to digital systems in manufacturing have been proposed. However, industrial applications of these reference architectures are scarce and it is difficult to compare and analyse them due to their various levels of application and different uses. In this study, we review and classify reference architectures used to support digital systems in manufacturing. Contributions of the paper include proposing criteria for a model to be referred to as a ‘reference architecture’, an overview and classification of the different perspectives on reference architectures in the literature, and a guideline to support practitioners, developers and academics in selecting a reference architecture.

1. Introduction

Digital technologies have revolutionised manufacturing. Their application yields more efficient industrial processes, improved product designs and enhanced capabilities of logistics and maintenance applications through a constant flow of information (Derigent et al., 2020). As manufacturing information systems become more interconnected and complex, there is a growing need for (system) architectures to guide their design and development (Pedone and Mezgár, 2018). The role of so called ‘reference architectures’ is to provide a structured template for forming such system architectures, and to provide specifications for system characteristics, design guidelines and standards. A large number of reference architectures for digital manufacturing have been proposed over the last decades (Derigent et al., 2020; Bader et al., 2019; Han, 2020; Megow, 2020; Soares et al., 2021). Although they are intended to simplify the design process, industrial applications are scarce. It is difficult to compare and evaluate reference architectures because they address various levels of application and different uses. In this study, we review the different ways that reference architectures are discussed and give practitioners, developers and academics a guideline to understand and select one based on their needs. Many existing methodologies to classify and compare reference architectures only focus on a particular domain and do not separate genuine reference architectures from system architectures, platforms or frameworks. While we concentrate on reference architectures, the proposed approach can also be modified to classify system architectures and analyse their relationship to platforms and frameworks. The key limitations we address include the lack of a distinction between reference architectures, system architectures, platforms and frameworks, the shortage of reported applications of reference architectures, and the need for frame of reference capable of classifying reference architectures across domains.

1.1. Digital manufacturing

Digital manufacturing describes ‘*the application of digital information [from multiple sources, formats, owners] for the enhancement of manufacturing processes, supply chains, products and services*’ (McFarlane et al., 2020). This subsection describes various paradigms related to digital manufacturing introduced in the literature. These paradigms

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[*] Corresponding author.
E-mail address: jk823@cam.ac.uk (J. Kaiser).

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have provided guidance on the use of digital systems in manufacturing over the last 40 years. In early work in manufacturing control systems, there were two main paradigms discussed, namely *Computer Integrated Manufacturing (CIM)* and *Holonic Manufacturing Systems (HMS)*. CIM aims to increase the efficiency of manufacturing processes through an integration of enterprise functions (Doumeingts et al., 1995; Yu et al., 2015). The holonic domain describes formations of autonomous and cooperative entities named holons, which characterise the whole spectrum of manufacturing entities. In recent years, several new paradigms have been introduced: the German government launched the *Industry 4.0* initiative to digitally transform the manufacturing domain through disruptive technologies (Rojko, 2017). So called *Smart Manufacturing* aims to enhance the application of networked information-based technologies to manufacturing and supply chain operations (Davis et al., 2012; Li et al., 2018; Mittal et al., 2019). The *Internet of Things (IoT)* uses a unique addressing scheme to enable collaboration among its components (Atzori et al., 2010). The Industrial Internet of Things (IIoT) concentrates on manufacturing processes and incorporates machine to machine (M2M) and industrial communication technologies for automation applications (Sisinni et al., 2018). Another way of modelling interconnected manufacturing systems is through the *Cyber–physical Systems (CPS)* paradigm. CPS embody collaborating computational elements which are connected to their surrounding physical world and its processes (Monostori, 2014; Pivoto et al., 2021). In this study, we concentrate on reference architectures which directly relate to these paradigms.

1.2. Reference architectures: a metamodelling perspective

The development, customisation and implementation of digital manufacturing systems has become increasingly complex for a variety of reasons. These systems are characterised by a tight coupling between elements and require an integrated view that includes both the digital and physical space. Formal modelling techniques can be used to aid the design and development of such systems. We have adopted the so called ‘metamodelling approach’ proposed by Karsai et al. (2000), which introduces an abstraction of the underlying model through a higher level of modelling, that contains information about its structure. Using this approach from a digital manufacturing perspective, reference architectures can be thought of as metamodels. In the literature, the term ‘reference architecture’ is applied to a variety of models, including system architectures, frameworks and platforms (Ding et al., 2021; Traganos et al., 2021). While these models relate to one another, there are significant differences which can, and has, led to ambiguity in the meaning of the term ‘reference architecture’. This subsection introduces the main modelling levels and provides a distinction between the different types of models relevant to this study.

While for digital manufacturing three modelling levels can be identified as shown in Fig. 1(a), which include the reference architecture, system architecture and the physical system, there are also other types of models discussed in the literature, such as platforms, frameworks and abstractions of reference architectures. Although it is beyond scope of this paper to study these other model types in detail, we note in Fig. 1(b) a rough indication of their relative position compared to the three modelling levels presented in Fig. 1(a): the *system level* represents the physical implementation of system components and interactions. The *model level* contains the system architecture, an abstraction of the specific underlying implemented system. Frameworks are more abstract than system architectures since they organise components and their interactions generally, and thus, they cannot be assigned to the model level. A higher level of abstraction is provided at the *meta level* which includes template structures in form of reference architectures. Platforms expand the technical aspects of reference architectures with business and operational views. Reference architectures can also be further generalised to meta abstractions, which consist of organisational approaches and ontologies. However, in most cases developers start on the meta or model level and transition to lower levels of abstraction when designing systems. We next provide the *working* definitions of the key terms used in this paper, starting with reference architectures because they represent the core of this study.

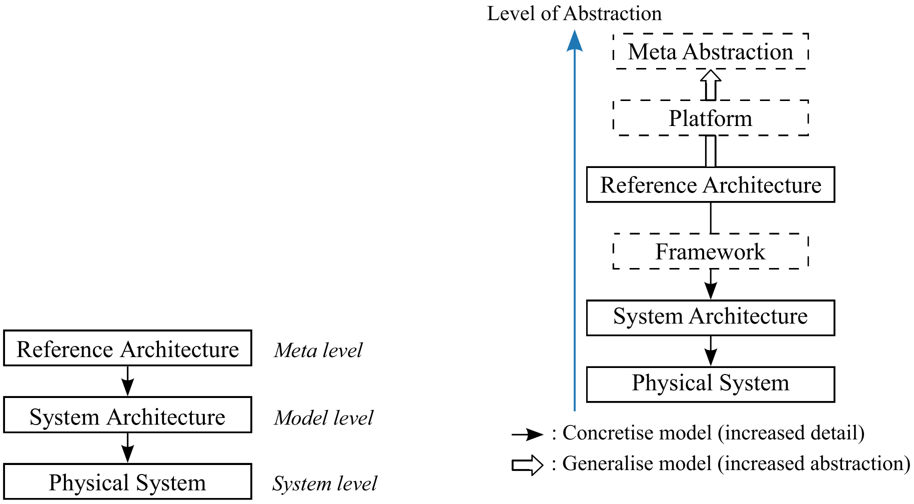
Reference architecture. *Reference architectures guide the design of system architectures by providing a structured template with common terminology*. They comprise a collection of characteristics of digital manufacturing systems, such as the relationship between control elements (e.g. hierarchical, or heterarchical) or how the system is decomposed into elements (e.g. service-oriented, or object-oriented). This is augmented with design guidelines, template solutions and standards. The characteristics of a reference architecture are dimensions, components or layers in conjunction with a certain longevity, whereby central publications and standards are accessible and referenced since their release. Reference architectures do not describe principles, concepts or technologies, such as agents (Paolucci and Sacile, 2005) and services (Papazoglou and Heuvel, 2007), which are utilised during the realisation of systems, although technologies can represent an essential feature of reference architectures.

System. *A digital manufacturing system is a real-world implementation of physical and digital components*, which includes machines, sensors, controllers and software. A system is a deployment of physical and digital components embodying the structures, relationships and interactions defined in the system architecture (using appropriate technologies). For example, this level is where a developer implementing a holonic system would choose whether to use the Java Agent Development Framework (JADE) or Erlang to achieve the desired system behaviour.

System architecture. *System architectures conceptualise the structure and function of an implemented system through an abstract description of its assets and how they relate to one another.* System architectures represent the model of an implemented system, which is dedicated to a specific task. Common models are Petri nets, flowcharts and diagrams, which map the relations between machines, sensors and controllers within the implemented system. There are three main characteristics of system architectures, namely they define the components of the implemented system, the relationships and interactions among those components, and the rules to manage those relationships and interactions. For example, the system architecture for a holonic manufacturing cell would include the holon specifications, diagrams to describe the relations and interactions between those holons, their interface descriptions, the communication patterns and relevant protocols. While reference architectures generally describe all system elements and their interactions that could be considered for different applications, system architectures consist of a subset of these elements selected for a specific application.

Framework. *Frameworks for digital manufacturing are reference architectures that have partially or fully prescribed sets of components or interaction patterns.* Frameworks describe specific instances of a reference architecture with strict design and implementation rules, and they can be used to develop multiple application-specific system architectures. Frameworks are characterised by constrained structures that outline the organisation of components and the interactions between them. While platforms tend to describe fully integrated solutions that consider the problem at large, frameworks are toolsets targeted at ad-hoc solutions for specific applications (e.g. IoT frameworks).

Platform. *Platforms for digital manufacturing combine design guidelines with an appropriate digital ecosystem.* Digital ecosystems describe the collaboration of stakeholders to exploit skills and knowledge for achieving a common goal (Otto et al., 2016). These platforms provide flexibility to enterprises by relying on services and technical components to orchestrate interactions between organisations and applications, and support the integration of new technologies (Directorate-General for Communications Networks Content and Technology and European Factories of the Future Research Association (EFFRA), 2015; Fraile et al., 2019; Gerrikagoitia et al., 2019). Apart from technical aspects, platforms include an operational and business view. Besides the



(a)

(b)

Fig. 1. (a) The three levels of the proposed metamodelling approach. (b) Rough indication of the relative position of platforms, frameworks and meta abstractions compared to the three levels of the metamodelling approach.

involvement of stakeholders (e.g. industry and software vendors) digital manufacturing platforms are characterised by the level of openness and standardisation, and a technical view. This technical view includes generic design guidelines or a reference architecture.

Meta abstraction. *Meta abstractions are organisational approaches and ontologies which provide core abstractions for reference architectures.* The meta abstraction layer contains the main interoperability features of a reference architecture. Ontologies define concepts and properties of reference architectures and the relations that hold between them (Giese et al., 2007; Horridge et al., 2011). Meta abstractions describe a set of core characteristics of the digital manufacturing system, such as service orientation or a holonic design approach. Reference architectures combine a subset of these characteristics augmented with design guidelines, terminologies, and technology recommendations. Meta abstractions are characterised by the selected type of organisation as well as the design concepts and principles.

There are several alternative modelling approaches that can be used to describe the relations between architectures and systems. Most notably, the UML metamodelling approach (Object Management Group, 2017) is widely adopted in research and industry, especially in the software development domain. Despite some similarities, there are two key differences upon comparison, specifically the proposed metamodelling levels are linked through specialisation and inheritance rather than instantiation, and there is no formalism for the reference architectures discussed in this study.

1.3. Paper outline

The paper is structured as follows. Section 2 identifies relevant models in the literature that refer to the term ‘reference architecture’, reviews previous approaches to classify, align and compare reference architectures, and examines applications of reference architectures in the literature. Section 3 proposes the methodology for classifying and analysing reference architectures. Section 4 performs the classification of selected reference architectures, its validation, and an analysis of the applicability of reference architectures, which is followed by a discussion of the results in Section 5. We conclude this paper by proposing future research endeavours.

2. Background

Reference architectures for digital manufacturing provide structure in the design of digital systems. Various research interests that fall under this topic ranging from technical issues, such as interoperability, to aspects concerning the whole enterprise. Much work has been done on classifying reference architectures. One of the limitations of this work to date has been the lack of a differentiation between the different types of models that are referred to as ‘reference architectures‘, and the small number of reported industrial applications. In this study a literature survey on reference architectures is conducted. Publications, including scientific contributions, standard documents and technical reports, were deemed to be relevant to this study if they propose a model which is termed ‘reference architecture’ by the authors or another publication. This section outlines research gaps in the study of architectures for industrial digital systems and establishes the focus of this study. We begin by presenting relevant models that are referred to as ‘reference architectures’, which is followed by a review of existing approaches to classify, align and compare reference architectures. Finally, the applicability problem is described.

2.1. Proposed models for digital manufacturing

Over the last decades, numerous models for digital manufacturing have been proposed and have frequently been referred to as ‘reference architectures’. We have gathered relevant models for our study based on two necessary criteria: (1) the model addresses at least one of the digital manufacturing paradigms, and (2) the model is being referred to as a ‘reference architecture’. Table 1 presents an overview of the models proposed in the literature.

Although the models proposed in Table 1 differ vastly in their features and the areas of manufacturing they address, they can be organised in terms of the digital manufacturing paradigms introduced in Section 1.1. In what follows, an overview of the key models related to those themes is provided.

Computer Integrated Manufacturing (CIM). Initial attempts to develop a digital manufacturing reference architecture were made as CIM began to emerge in the 1980s (Rembold et al., 1985). Whereas most models only focus on specific aspects of CIM, two models address a global enterprise integration (Doumeingts et al., 1995): PERA (Williams, 1994) integrates control and enterprise systems through a hierarchical model of production and business processes including components of the control and information system. It characterises a core element of ANSI/ISA-95 (IEC 62264) (IEC, 2003), which forms the basis for several successors. CIMOSA (Kosanke, 1995) models the lifecycle of the integrated enterprise by separating functional, information, resource and organisational concerns.

Table 1
Proposed digital manufacturing models that are referred to as ‘reference architectures’.

No.	Model	Year	Publication
1	Computer-Aided Manufacturing - International (CAM-I)	1979	Doumeingts et al. (1995)
2	Integrated Computer-Aided Manufacturing (ICAM)	1981	Doumeingts et al. (1995)
3	Graphs with Results and Actions Interrelated (GRAI)	1984	Chen and Doumeingts (1996)
4	Knowledge-based Real Time Supervision in CIM (ESPRIT Project 932)	1988	Doumeingts et al. (1995)
5	Manufacturing Management and Control System (MMCS)	1988	Moss (1989)
6	PROCOS Generic CIM Architecture	1988	Moss (1989)
7	Integrated Manufacturing Planning and Control System (IMPACS)	1991	Doumeingts et al. (1995)
8	Computer Integrated Manufacturing Open System Architecture (CIMOSA)	1992	Kosanke (1995)
9	GRAI Integrated Method (GIM)	1992	Vallespir et al. (1992)
10	Purdue Enterprise Reference Architecture (PERA) / ISA-95 / IEC 62264	1993	Williams (1994), IEC (2003)
11	Stair-like CIM System Architecture (SLA)	1997	Chen and Tseng (1997)
12	Product Resource Order Staff Architecture (PROSA)	1998	Brussel et al. (1998)
13	Adaptive Agent-based Architecture for Intelligent Manufacturing (MetaMorph) / IEC 61499–1	1999	Maturana et al. (1999), IEC (2012)
14	Holonic Component-Based Architecture (HCBA)	2000	Chirn and McFarlane (2000)
15	Open Architecture for Holonic Cooperation and Autonomy (OAHCA)	2000	Fletcher et al. (2000)
16	Adaptive Holonic Control Architecture (ADACOR)	2006	Leitão and Restivo (2006)
17	Delegate Multi-Agent System (D-MAS)	2008	Verstraete et al. (2008)
18	Product, Resource, Order and Simulation Isoarchic Structure (PROSIS)	2009	Pujo et al. (2009)
19	International Telecommunication Union IoT (ITU-IoT)	2012	ITU-T (2012)
20	Smart Manufacturing Leadership Coalition (SMLC) Smart Manufacturing Platform	2012	Davis et al. (2012)
21	IoT Architectural Reference Model (IoT-ARM / IoT-A)	2013	Bauer et al. (2013)
22	‘Surveillance Active Ferroviaire’ (SURFER)	2013	Mortellec et al. (2013)
23	Virtual Fort Knox (VFK)	2013	Holtewert et al. (2013)
24	Cisco IoT	2014	Cisco Systems (2014)
25	Cyber–Physical Production Systems (CPPS)	2014	Monostori (2014)
26	Dynamic Architecture for an Optimised and Reactive Control of Flexible Manufacturing Scheduling (ORCA-FMS)	2014	Pach et al. (2014)
27	5C	2015	Lee et al. (2015)
28	ADACOR^2	2015	Barbosa et al. (2015)
29	Future Internet Technologies for Manufacturing Industries (FITMAN)	2015	Lazaro et al. (2015)
30	Industrial Internet Consortium (IIC) Industrial Internet Reference Architecture (IIRA)	2015	Industrial Internet Consortium (2015)
31	Smart Manufacturing Networks (SMN)	2015	Papazoglou et al. (2015)
32	Vertical Integration Architecture (VIA)	2015	Pérez et al. (2015)
33	WSO2 IoT	2015	Fremantle (2015)
34	Anthropocentric Cyber–Physical Reference Architecture for Smart Factories (ACPA4SF)	2016	Pirvu et al. (2016)
35	CPS Architecture for Intelligent Manufacturing	2016	Liu and Jiang (2016)
36	Holonic Hybrid Control Model (H^{2}CM)	2016	Indriago et al. (2016)
37	Industrial Data Space (IDS)	2016	Otto et al. (2016)
38	Industrial Value Chain Reference Architecture (IVRA)	2016	Industrial Value Chain Initiative (2016)
39	National Institute of Standards and Technology (NIST) Smart Manufacturing Ecosystem (SME)	2016	Lu et al. (2016a)
40	NIST Service-Oriented Smart Manufacturing Architecture (NIST SOA)	2016	Lu et al. (2016b)
41	‘Plattform Industrie 4.0’	2016	Federal Ministry for Economic Affairs and Energy (2016)
42	Dynamic Hybrid Control Architecture (POLLUX)	2016	Jimenez et al. (2017)
43	Service-oriented Holonic Manufacturing System (SoHMS)	2016	Quintanilla et al. (2016)
44	Arrowhead Framework	2017	Varga et al. (2017)
45	Intelligent Manufacturing System Architecture (IMSA)	2017	Wei et al. (2017)
46	NIST Framework for Cyber–Physical Systems (NIST F-CPS)	2017	Griffor et al. (2017)
47	Reference Architecture Model Industry 4.0 (RAMI 4.0)	2017	IEC (2017)
48	Stuttgart IT Architecture for Manufacturing (SITAM)	2017	Kassner et al. (2017)
49	3C	2018	Ahmadi et al. (2018)
50	8C	2018	Jiang (2018)
51	Activity Resource Type Instance Architecture (ARTI)	2018	Valckenaers (2019)
52	Alliance for Internet of Things Innovation (AIOTI) High Level Architecture (HLA)	2018	Alliance for Internet of Things Innovation (2018)
53	Big Picture	2018	ISO/TR (2018)
54	Embedded Agent CPS Architecture (Embedded Agent CPSA)	2018	Marques et al. (2018)

(*continued on next page*)

Table 1 (*continued*).

No.	Model	Year	Publication
55	Integration of Informatisation and Industrialisation (iI&I)	2018	Li et al. (2018)
56	Internet of Things Reference Architecture (IoT RA)	2018	ISO/IEC (2018)
57	Blockchain enabled CPS Architecture (BCPS)	2019	Lee et al. (2019)
58	Digital Manufacturing on a Shoestring (Shoestring)	2019	McFarlane et al. (2020), Hawkridge et al. (2022)
59	Industrial Internet Integrated Reference Model (I3RM)	2019	Fraile et al. (2019)
60	Laboratory for Handling, Assembly and Pneumatics Smart Factory (LASFA)	2019	Resman et al. (2019)
61	World Wide Web Consortium (W3C) Web of Things (WoT)	2019	Lagally et al. (2021)
62	Aligned Reference Architecture for Digital Factories (ARADF)	2020	Soares et al. (2020)
63	Cyber–Physical Architecture of Internet of Things (CPA IoT)	2020	Farsi et al. (2020)
64	High Level Architecture for the Factory Of the Future (HLA FOF)	2020	Havard et al. (2020)
65	Industry 4.0 Virtual Automation Bus Architecture (BaSys)	2020	Kuhn et al. (2020)
66	KSTEP	2020	Han (2020)
67	Manufacturing Blockchain of Things (MBCoT) Architecture	2020	Zhang et al. (2020)
68	Reference Architecture Model Edge Computing (RAMEC)	2020	Willner and Gowtham (2020)
69	Scandinavian Smart Industry Framework (SSIF)	2020	Han (2020)
70	Smart Manufacturing Standards Landscape (SM2)	2020	ISO/IEC (2020)
71	Zero Defects Manufacturing Platform (ZDMP)	2020	Nazarenko et al. (2020)
72	Advanced Manufacturing Research Centre (AMRC) Factory+	2021	Coles et al. (2021)
73	Digital Twin as a Service (DTaaS) Architecture Reference Model	2021	Aheleroff et al. (2021)
74	IBM Industry 4.0 Reference Architecture (IBM I4.0)	2021	IBM (2021)
75	ISO-IEC Joint Working Group - Unified Reference Model for Smart Manufacturing (ISO-IEC JWG21)	2021	IEC (2022)
76	Q-Holonic-Based Architecture (QHAR)	2021	Macherki et al. (2021)
77	Reference Model for Smart Factories (RMSF)	2021	Soares et al. (2021)
78	National Bureau of Standards (NBS) Model	N/A	Doumeingts et al. (1995)

Holonic Manufacturing Systems (HMS). The holonic paradigm was introduced in the 1990–2010s to increase the resilience of manufacturing systems to rapid changes in their environment. Early adoptions to the manufacturing domain was performed by Christensen (1994). Based on this initial architecture, PROSA (Brussel et al., 1998) was developed, which specifies four types of holons for the different resources and roles that exist on the production line. Besides, two other reference architectures have been proposed: HCBA (Chirn and McFarlane, 2000) provides autonomous, modular and cooperative building blocks to enable a reconfigurable manufacturing system. ADACOR (Leitão and Restivo, 2006) relies on a supervisor holon to alternate between a centralised and a decentralised architecture, thus leading to rapid responses to unexpected disturbances.

Emerging digital technologies. For the last 25 years, a range of new technologies have been developed to support the design of manufacturing information systems, such as services (Papazoglou and Heuvel, 2007), digital twins (Tao et al., 2018) and software agents (Paolucci and Sacile, 2005). Most notably, services represent a key feature for numerous reference architectures that aim towards a horizontal integration. They facilitate the design of networked systems through a standard-based loosely coupled form of distributed computing. For example, IBM Industry 4.0 (IBM, 2021) leverages services to ease the integration with external applications.

Industry 4.0 and Smart Manufacturing. While the ISA-95 standard envisions a strict vertical integration of manufacturing and enterprise systems, two main paradigms, namely Smart Manufacturing (Davis et al., 2012; Li et al., 2018; Mittal et al., 2019) and Industry 4.0 (Rojko, 2017), aim to achieve a horizontal integration by developing decentralised connected information systems. Such systems enhance the flexibility and efficiency across the value chain (Davis et al., 2012; Mittal et al., 2019). RAMI 4.0 (IEC, 2017) supports the design of components through standards and the specification of lifecycle, technical and organisational functions. It encapsulates assets, such as machines and products, into an administration shell, providing a standardised interface and data storage. NIST SME (Lu et al., 2016a) provides an overview of relevant standards for digital manufacturing systems. This model separates between business, production and product functions through devoted lifecycles. Both RAMI 4.0 and NIST SME are built upon ISA-95 and augment it with features for a horizontal integration, such as lifecycle models and decentralisation.

Internet of Things (IoT) and Cyber-physical Systems (CPS). Several approaches have focused on developing connected information systems: IoT deals with the integration of technologies with communication systems. Besides general IoT models, multiple reference architectures explicitly include the development of manufacturing systems. Above all, IIRA (Industrial Internet Consortium, 2015) is a standard-based open architecture that identifies four main concerns, namely business, usage, functional and implementation, to aid the development of IIoT applications. Conversely, CPS focus on the development of components for decentralised information systems. 5C (Lee et al., 2015) comprises five levels to characterise CPS components, including interfaces, analytics and self-configuration.

2.2. Industrial applications of reference architectures

Although numerous ‘reference architectures’ are proposed in the literature, reports of industrial applications are scarce. Gomez-Gasquet et al. (2010) derive requirements for the design of an agent-based production scheduling system based on the functional view of CIMOSA. Unver (2013) designs a solution based on ISA-95 that integrates the planning level with the shopfloor. This solution serves as a repository of operational and enterprise data. Swert et al. (2006) extend PROSA for the purpose of railroad control, while Barbosa et al. (2016)

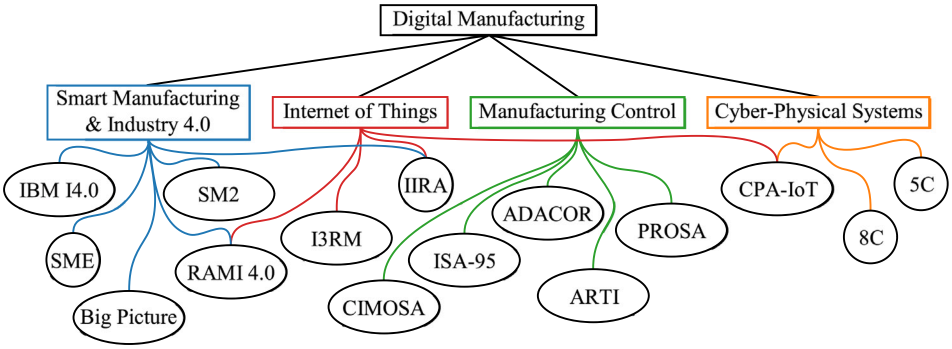


Fig. 2. The various relations of reference architectures to different digital manufacturing paradigms. Manufacturing control includes both CIM and holonic reference architectures.

implement ADACOR using JADE and OPC UA for a small-scale production system. Kruger and Basson (2017) use Erlang to concretise PROSA for a holonic controller of a manufacturing cell. Martínez et al. (2020) adopt the IoT-ARM domain model for the virtualisation of autonomous underwater vehicles. Alexakos et al. (2019) develop a system architecture based on IIRA for a small-scale living lab for smart energy using open-source technologies. In an attempt to concretise RAMI 4.0, Grangel-Gonzalez et al. (2016) create a semantic map of the administration shell with a Resource Description Framework. Melo et al. (2021) propose a control device for Industry 4.0 applications that integrates the asset, integration and communication layer of RAMI 4.0 via OPC UA. Contreras et al. (2017) argue that for a complete Industry 4.0 application, additional strategies need to be combined with RAMI 4.0. The authors use OPC UA and AutomationML in combination with a holonic approach to develop a digital manufacturing system. Moreover, Ye and Hong (2018) also rely on OPC UA and AutomationML to derive a framework for manufacturing solutions based on RAMI 4.0. Finally, Hawkridge et al. (2021) and Kaiser et al. (2022a) demonstrate the application of the Shoestring reference architecture.

While these examples show that some reference architectures have been applied in practice, this on its own is not a suitable indicator for their applicability. That is, a reference architecture without any publications about its application can be as applicable as one with multiple scientific papers. We identify three potential explanations: first, some work may be confidential and thus not reported in the literature. Additionally, industrial applications are not described in scientific publications but in technical and commercial reports. Third, a set of reference architectures may not be properly aligned with actual industrial needs.

2.3. Classification and comparison approaches

There are a number of approaches suggested in the literature that are helpful in trying to classify digital manufacturing reference architectures: Monostori (2014) relates CPS to other digital manufacturing paradigms, such as digital factories and holonic manufacturing. Weyrich and Ebert (2016) categorise RAMI 4.0 and IIRA as IoT reference architectures, whereas Kassner et al. (2017) separate these two models by describing three distinct classes, abstract frameworks, cross-domain reference architectures, and concrete manufacturing IT architectures. Li et al. (2018) and Soares et al. (2021) developed similar classes for Smart Manufacturing reference architectures. Moghaddam et al. (2018) approach a consistent reference architecture that rationalises and envelopes the views of numerous models. Bader et al. (2019) select reference architectures based on the total number of searches through internet search engines. Finally, Kaiser et al. (2022b) classifies reference architectures based on common features sets.

Three main approaches for comparing and aligning reference architectures can be identified: the first approach selects a small subset of reference architectures and performs a feature analysis which is followed by an alignment of functions and components (Pedone and Mezgár, 2018; Megow, 2020; Pivoto et al., 2021; Fraile et al., 2019; Alliance for Internet of Things Innovation, 2018; Moghaddam et al., 2018; Federal Ministry for Economic Affairs and Energy, 2018; Nakagawa et al., 2021). The alignment is severely influenced by the reference architecture that is chosen as a baseline. That is, the set of candidate models for the comparison mainly describe similar levels and uses. The second approach introduces a feature map (Soares et al., 2020; Guth et al., 2018; Nakagawa et al., 2021), which is created based on commonalities among selected reference architectures. The third approach reduces reference architectures to their core dimensions (Han, 2020; Soares et al., 2020). These so called ‘skeleton models’ form the basis for the comparison. While the second and third approach are more general and thus allow for a larger subset of reference architectures to be compared, an in-depth analysis becomes increasingly difficult. To maximise the subset of reference architectures, this study applies qualitative evaluation measures.

Comparing and evaluating reference architectures is challenging because they address different levels and uses. Specifically, proposed models may relate to a different metamodelling level shown in Fig. 1(a) and might characterise system architectures or frameworks. Furthermore, many reference architectures are related to other models and provide templates for various applications, which yields a cumbersome separation and classification. Fig. 2 illustrates a set of reference architectures including their relationships to different digital manufacturing paradigms. While some reference architectures can be solely linked to one paradigm, others provide additional views and enable the developer to deal with different aspects of a digital manufacturing domain. For example, RAMI 4.0 issues the organisation of systems within an enterprise but also includes a functional view on connected devices.

2.4. Research gaps

There has been a lot of research on reference architectures, including their classification, comparison and analysis. However, there are a number of key limitations of the work to date, which we aim to address in this study: first, current approaches lack a clear distinction between reference architectures, system architectures, platforms and frameworks. Second, approaches reported in previous studies have not had sufficient detail to allow for the classification of reference architectures across multiple digital manufacturing domains. Further, there is a need for a general classification approach, which is capable of classifying a wide range of (heterogeneous) reference architectures. Finally, the shortage of industrial applications has not been addressed so far despite the large number of proposed models. The rationale behind this study is to provide a clear distinction between ‘genuine’ reference architectures and system architectures, frameworks and platforms. We further classify and analyse the applicability of the genuine reference architectures to help developers improve their applicability and practitioners to select one based on their needs.

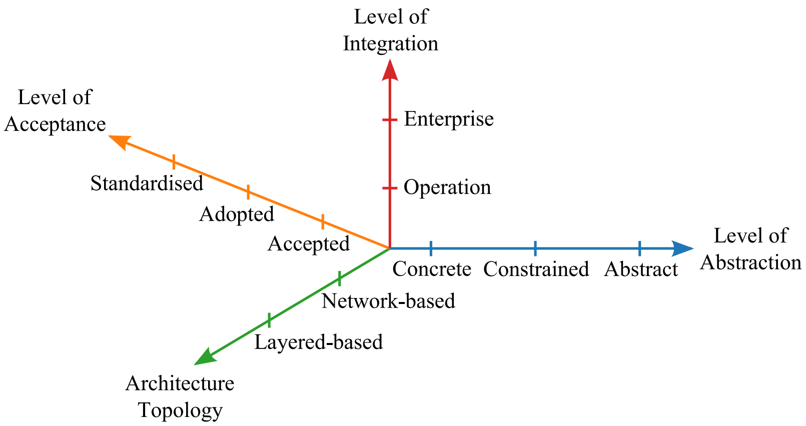


Fig. 3. Axes for classifying reference architectures.

3. Methodology

This section outlines the methodology of this study. Specifically, we propose a frame of reference to allow for the classification of reference architectures, and introduce measures to compare them. To guide practitioners in selecting a reference architecture based on their needs, we further analyse their applicability for industrial use.

Concretely, the methodology consists of four steps:

1. Definition: define selection criteria to separate reference architectures from system architectures, platforms and frameworks
2. Classification: classify reference architectures using a general frame of reference independent from a particular model
3. Validation: validate the classification by comparing reference architectures that belong to the same category
4. Analysis: analyse the applicability of reference architectures

Each of the individual steps of the proposed methodology are now outlined.

3.1. Definition of selection criteria

As indicated earlier, not every model that is termed ‘reference architecture’ meets the characteristics of a reference architecture. Here, we apply the definitions and characteristics of reference architectures, system architectures, platforms and frameworks stated in Section 1.2 to filter the list of proposed models for manufacturing information systems. We classify each proposed model in terms of a set of options each with its own characteristics. Models which do not meet all characteristics of any option will be rejected and are not considered for further investigation.

3.2. Classification frame of reference

A first guidance for adopting an appropriate reference architecture is provided through a frame of reference, which helps to classify digital manufacturing reference architectures. This classification frame, which is illustrated in Fig. 3, consists of four axes, each representing an indicator for applicability. A *class* of reference architectures is a 4D tuple containing one tick label of each axis. A *category* of reference architectures combines multiple classes. We argue that classes remain mutually exclusive and unweighted to simplify the selection process for practitioners. Therefore, based on the chosen axes, there are 36 different classes. *Only the topmost view depicting the main features of a reference architecture is considered for the classification*. Some standardised reference architectures also include additional models, which, for instance, represent the data flow among components. However, these additional models are not always provided and can thus not be compared across reference architectures. In the following, the classification axes are described in detail.

Level of Abstraction. The level of abstraction axis is based on the metamodelling approach and subdivides reference architectures into three distinct classes: *concrete* reference architectures entail detailed design and implementation guidelines, which innately yield standards recommendations. While *constrained* reference architectures prescribe standards, design instructions or certain system characteristics, *abstract* ones are neither limited by standards nor design and implementation rules.

Level of Integration. The level of integration helps to identify the application area of reference architectures. There are two main levels of integration, *operation* and *enterprise*. For the former, reference architectures concentrate on the integration at an operation level for the design of manufacturing information systems. For the latter, the focus lies on the integration of enterprise functions and processes.

Architecture Topology. The architecture topology groups reference architectures subject to their respective system design process. It is based on the design methodologies for engineering systems (Moses, 2010), namely top-down structured, layered and network-based. While a top-down approach is inherently ill-suited for a reference architecture due to its inflexibility, a *network-based* reference architecture yields a system that consists of a decentralised network of connected components. Conversely, a *layered-based* reference architecture describes a hierarchical design process where elements of a layer can be seen as part of group and parents can readily change, thus leading to more development paths from top to bottom. If a reference architecture combines both topologies, only the key features are considered for the classification. For example, ADACOR can form both hierarchical (layered) and heterarchical (network) structures, but, essentially, its key feature are interconnected holons enabling the formation of these structures. Therefore, ADACOR would be classified as network-based.

Level of Acceptance. The level of acceptance characterises the maturity of reference architectures. A given reference architecture has been *accepted* for a conference or for publication in an academic journal, *adopted* by developers or practitioners to design and implement digital manufacturing systems, or *standardised* by means of an official standard document.

Reference architectures can only be analysed relatively. However, not all classes can be compared to one another. While the architecture topology and the level of integration and abstraction address inherently different features, the key elements of a reference architecture do not change with increasing maturity. Hence, the classes of standardised, adopted and accepted reference architectures can be merged to a category. To validate the proposed classification, the reference architectures of these resulting categories are compared.

3.3. Validation measures

To validate the classification, we compare reference architectures within the same category. Multiple classes are merged into categories to increase the set of reference architectures that can be compared. However, practitioners should rely on the classes when selecting a reference architecture to meet their requirements more accurately. Two general validation measures are defined which are applicable to all reference architectures:

(1) *Meta conformity*: the extent to which the meta abstractions of all reference architectures of a given category are similar in terms of their type of organisation and design concepts
(2) *Feature overlap*: the degree to which the characteristics of reference architectures within a given category address overlapping features of digital manufacturing systems

Relying on one of the three comparison and alignment approaches presented in Section 2.3 is not feasible in this study. A detailed feature mapping and an alignment of functions are out of scope for the extensive list of models considered in this study. Furthermore, skeleton models can only be developed for layered-based reference architectures because the network-based ones neither have dimensions nor views.

3.4. Analysing the applicability of reference architectures

For a better understanding of reference architectures and how practitioners and developers can select one based on their needs, we compare the applicability of reference architectures in this study. The *applicability of a reference architecture* refers to *the capability of the reference architecture to be adopted and applied in practice.* One interpretation of the applicability is the overall number of design decisions that need to be made. We define four criteria that indicate the applicability of a reference architecture:

(1) *Range of development pathways*: indicating how straightforward the design process is when using a reference architecture
(2) *Size of application area*: describing how broadly a reference architecture can be applied
(3) *Availability of standards and implementation guides*: outlining whether a reference architecture includes standards and implementation guides
(4) *Provision of submodels*: defining whether a reference architecture proposes additional submodels — models that prescribe certain system features (e.g. representation of the data flow between systems) or behavioural characteristics

For example, a reference architecture has a large range of development pathways if few design guidelines are provided and many design decisions are required to fully describe a system. The inclusion of standards, design guidelines, submodels, or the prescription of certain behavioural characteristics of systems increase the applicability of a reference architecture, since the design is more prescribed and less decisions have to be made by the developer. We differentiate between structural and process standards. Guidelines are essentially process standards. Conversely, a high abstraction tends to increase the area of application. The applicability of reference architectures is maximised for a small range of development pathways and a large area of application in combination with standards, design guidelines and submodels.

4. Results

A wide range of models that are commonly termed 'reference architectures' has been reviewed in this study. We provided a distinction between genuine reference architectures and system architectures, frameworks and platforms by outlining their key characteristics. Out of 78 model proposals 36 'genuine' reference architectures are identified, and classified using a frame of reference independent from a particular model or digital manufacturing domain. The resulting classes are valid since the reference architectures they contain are similar in terms of their features and meta abstractions. Analysing the applicability of reference architectures within those classes reveals that reference architectures which include detailed design guidelines and standards require the least effort when being adopted by developers.

Table 2
Selected system architectures, frameworks and platforms.

System architectures	Frameworks	Platforms
CPA IoT (Farsi et al., 2020)	3C (Ahmadi et al., 2018)	FITMAN (Lazaro et al., 2015)
Embedded Agent CPSA (Marques et al., 2018)	Meta-Morph (Maturana et al., 1999; IEC, 2012)	IDS (Otto et al., 2016)
HLA FOF (Havard et al., 2020)	Factory+(Coles et al., 2021)	NIST F-CPS (Griffor et al., 2017)
BaSys (Kuhn et al., 2020)	ACPA4SF (Pirvu et al., 2016)	'Plattform Industrie 4.0' (Federal Ministry for Economic Affairs and Energy, 2016)
MBCoT (Zhang et al., 2020)	Arrowhead Framework (Varga et al., 2017)	SMLC (Davis et al., 2012)
MMCS (Moss, 1989)	D-MAS (Verstraete et al., 2008)	SMN (Papazoglou et al., 2015)
POLLUX (Jimenez et al., 2017)	ORCA-FMS (Pach et al., 2014)	VFK (Holtewert et al., 2013)
SURFER (Mortellec et al., 2013)	GIM (Vallespir et al., 1992)	ZDMP (Nazarenko et al., 2020)
VIA (Pérez et al., 2015)	GRAI (Chen and Doumeingts, 1996)	
	H^{2}CM (Indriago et al., 2016)	
	IoT ARM (Bauer et al., 2013)	
	LASFA (Resman et al., 2019)	
	OAHCA (Fletcher et al., 2000)	
	PROCOS (Moss, 1989)	
	PROSIS (Pujo et al., 2009)	
	SoHMS (Quintanilla et al., 2016)	
	SITAM (Kassner et al., 2017)	

4.1. Selection of reference architectures

Before conducting the classification, the list of models proposed in the literature that are labelled 'reference architectures' is filtered. Table 2 shows a list of those models that are not reference architectures but in fact are system architectures, frameworks and platforms. In Table 3 the remaining models which are genuinely reference architectures according to the definitions in Section 1.2 are further classified using Fig. 3. Since for a handful of models publications are not available, these models do not satisfy all criteria of a reference architecture and are therefore not considered for further study.

Table 3
Classification of reference architectures and the resulting ten categories (A–J).

	Network-based		Layered-based	
	Operation	Enterprise	Operation	Enterprise
Abstract	ARTI (Valckenaers, 2019) *PROSA* (Brussel et al., 1998) QHAR (Macherki et al., 2021) A	–	5C (Lee et al., 2015) BCPS (Lee et al., 2019) Cisco IoT (Cisco Systems, 2014) CPS-A IM (Liu and Jiang, 2016) E	8C (Jiang, 2018) ARADF (Soares et al., 2020) *CIMOSA* (Kosanke, 1995) DTaaS (Aheleroff et al., 2021) IVRA (Industrial Value Chain Initiative, 2016) iI&I (Li et al., 2018) RMSF (Soares et al., 2021) SLA (Chen and Tseng, 1997) H
Constrained	ADACOR^{2} (Barbosa et al., 2015) *ADACOR* (Leitão and Restivo, 2006) HCBA (Chirn and McFarlane, 2000) B	NIST SOA (Lu et al., 2016b) D	AIOTI HLA (Alliance for Internet of Things Innovation, 2018) **ITU-IoT** (ITU-T, 2012) **IoT RA** (ISO/IEC, 2018) RAMEC (Willner and Gowtham, 2020) WSO2 IoT (Fremantle, 2015) F	**Big Picture** (ISO/TR, 2018) *IIRA* (Industrial Internet Consortium, 2015) I3RM (Fraile et al., 2019) IMSA (Wei et al., 2017) KSTEP (Han, 2020) SME (Lu et al., 2016a) **PERA/ISA-95** (Williams, 1994; IEC, 2003) **RAMI 4.0** (IEC, 2017) **SM2** (ISO/IEC, 2020) I
Concrete	WoT (Lagally et al., 2021) *ADACOR/JADE** (Barbosa et al., 2016) *PROSA/Erlang** (Kruger and Basson, 2017) C	–	Shoestring (McFarlane et al., 2020; Hawkridge et al., 2022) G	IBM Industry 4.0 (IBM, 2021) *IIRA/Thingsboard** (Alexakos et al., 2019) J

Accepted
*Adopted/concretised using a specific approach or technology**
Standardised

4.2. Classification of reference architectures

Out of the 36 models identified as reference architectures, which are classified in Table 3, half of them concentrate on the integration of enterprise functions. These reference architectures are abstract, such as CIMOSA and IVRA, or constrained, including IIRA, RAMI 4.0 and ISA-95. They are generally layered-based rather than network-based. Such layered-based approaches enable a straightforward identification and specification of functions of digital manufacturing systems within the context of their enterprise. In contrast, layered-based reference architectures that focus on the integration at an operation level generally revolve around the concepts of CPS and IoT, specialising on the development of highly interoperable components. Examples include the abstract 5C reference architecture as well as the standardised IoT RA and ITU-IoT. Further, most network-based reference architecture deal with the integration at an operation level and are based on the holonic paradigm, such as PROSA, ADACOR and HCBA. While network-based reference architectures are constrained by certain system characteristics, layered-based ones merely contain standard specifications or characterise standards themselves. It is noteworthy to mention that only a fraction of reference architectures comprise detailed design and implementation guidelines. However, abstract and constrained approaches can be systematically concretised by combination with a particular technology, such as using Erlang for PROSA, which greatly reduces the effort of designing systems.

Over the years, several reference architectures have become predecessors or feature providers for subsequent models. As illustrated in Fig. 4, ISA-95, RAMI 4.0 and IIRA provide core elements for various subsequent reference architectures, while PROSA, ADACOR and the 5C reference architecture have evolved into proper predecessors. It is important to note that adding features or using a reference architecture as a basis for a new one does not yield different architecture topologies. Such pathways may only alter the level of abstraction and integration of a reference architecture.

4.3. Validation of the classification approach

To validate the classification, the reference architectures within the same category are compared and evaluated using the measures defined in Section 3.3. As mentioned above, we merge standardised, adopted and accepted reference architectures with the other classes, because the different features reference architectures possess do not change with increasing maturity. Since reference architectures can only be assessed relatively, the empty classes and those, which only contain a single reference architecture, cannot be validated. In the following, the reference architectures of the categories containing more than one reference architecture are evaluated.

A: Abstract—Network-based—Operation. All meta abstractions for the given reference architectures describe the same core characteristic, namely the holonic paradigm. ARTI generalises PROSA for non-manufacturing applications by replacing holons with activity types and instances, but ARTI resembles many features of its predecessor (Valckenaers, 2019). While PROSA and ARTI dedicate different holons to specific tasks, QHAR introduces the Q-Holon, a generic element capable of representing any entity or actor by configuring its attributes and operations. However, the Q-Holon can be mapped

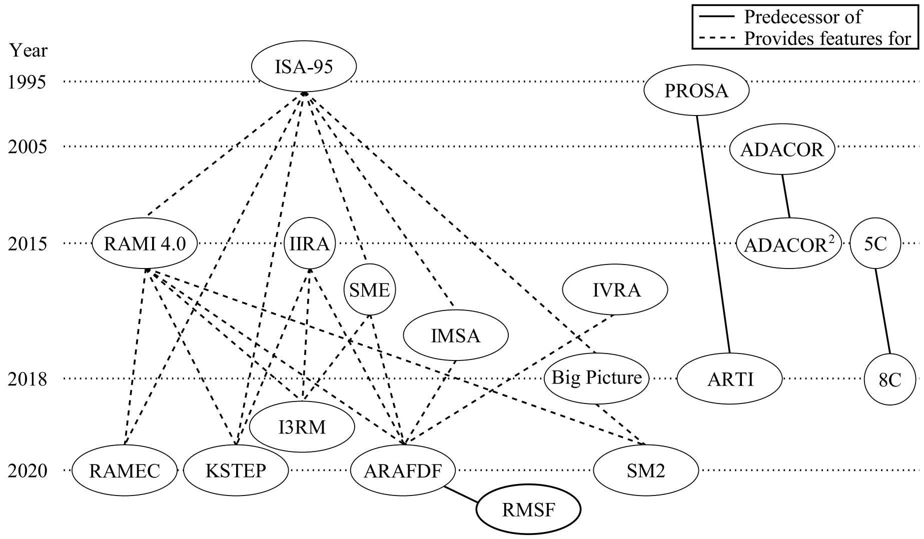


Fig. 4. Evolution of digital manufacturing reference architectures and their successors.

to the holons suggested by PROSA and ARTI (Macherki et al., 2021). Thus, QHAR shares the majority of their features. The activity types and instances of ARTI are not separate entities but modelled via the attributes of the Q-Holon.

B: Constrained—Network-based—Operation. All meta abstractions are characterised by the holonic design approach. ADACOR^2 extends ADACOR through a 2D self-organisation model (Barbosa et al., 2015). While ADACOR uses a supervisor in conjunction with the basic holons for coordinating and optimising the operation in decentralised topologies, HCBA only relies on product and resource holons. Specifically, HCBA characterises an inherently distributed approach, whereas both ADACOR^2 and ADACOR are capable of forming hierarchical and heterarchical systems.

C: Concrete—Network-based—Operation. Both PROSA/Erlang and ADACOR/JADE are based on a holonic design approach. The basis for WoT forms a consumer-thing interaction, where consumers are computational devices and things represent an abstraction of a virtual or physical resource. The things described by WoT are similar to resource holons, whereas the behaviours of staff, product and supervisor holons are performed by the consumer. WoT was designed for a plethora of IoT applications, while ADACOR/JADE and PROSA/Erlang focus on the manufacturing domain. Furthermore, WoT does not prescribe a specific technology, whilst the concrete ADACOR and PROSA instances demand the use of JADE and Erlang.

E: Abstract—Layered-based—Operation. Every reference architecture in this category characterises a hierarchical core structure which shares similarities with the OSI model (ITU-T, 1994). 5C and Cisco IoT describe the system development in terms of layers: the lower layers deal with connectivity and converting data to information, whereas the upper layers handle analytics and decision making. Cisco IoT includes one additional bottom layer describing the various physical devices that can be interacted with. Further, CPS-A IM reduces the features of the other reference architectures to three layers. The main difference is that processing and interpreting data is not handled on edge. Finally, BCPS restructures the 5C layers and details the impact of blockchain technology (Lee et al., 2019).

F: Constrained—Layered-based—Operation. All meta abstractions in this category are characterised by a hierarchical architecture based on the OSI model. While the application, service support and network layer are equal between the AIOTI HLA functional model and ITU-IoT, the latter provides additional features, such as a layer for describing device and gateway capabilities and security capabilities that span across all layers (Alliance for Internet of Things Innovation, 2018). Similar to ITU-IoT, the IoT RA also includes cross-domain aspects such as connectivity and interoperability. In contrast to ITU-IoT and AIOTI HLA, IoT RA provides a more detailed view by separating the user domain from the application. Furthermore, WSO2 IoT has levels and cross-cutting functions similar to ITU-IoT and IoT RA. Finally, the cross-cutting concerns and layers of RAMEC resemble many features of the other reference architectures in this category, but RAMEC provides additional hierarchy levels to distinguish where the data processing takes place.

H: Abstract—Layered-based—Enterprise. While all reference architectures describe hierarchies for the design of digital manufacturing systems, there are some differences when analysing the feature overlap. 8C extends 5C by adding integrated product and value chains, the role of the customer during the product design, and the product traceability record. There is an overlap between the cyber dimension of ARAFDF and the first five layers of 8C, whereas only the integration of product and value chains can be directly aligned. The generic views proposed by CIMOSA for developing enterprise models are represented by various aspects of other reference architectures in this category. Moreover, DTaaS uses a 3D model to capture key aspects of the digital twin. Generally, the information is arranged differently compared to other reference architectures in this category. For instance, 8C includes the digital twin concept in a layer. The layers of DTaaS can be aligned with the product lifecycle of the other reference architectures. Its iterative value lifecycle can be compared to the lifecycles presented by ARAFDF and 8C (Aheleroff et al., 2021). Next, IVRA consists of a collection of communicating autonomous units containing an asset, an activity and a management view. The organisation of those units is hierarchical and their levels, integrated product and value chains can be mapped to the cyber, lifecycle and physical dimension of ARAFDF and the 8C layers (Soares et al., 2020). iI&I models the maturity of enterprise integration through the use of information and industrial technologies in business and organisational processes. It reuses the management view of IVRA, and its organisation and business dimensions depict many features of 8C and ARAFDF (Li et al., 2018). RMSF extends ARAFDF and thus it also shows similarities to 8C, DTaaS and iI&I (Soares et al., 2021). Lastly, the project lifecycle, realisation and views of SLA can be aligned to the core dimensions of CIMOSA. SLA also characterises central aspects of other reference architectures. For example, the information and organisation subsystems can be mapped to the human and cyber dimensions of ARAFDF.

Table 4
Analysis of the applicability of the ten reference architecture categories (A–J). Each of the four criteria indicates how applicable the reference architectures within a category are.

Applicability criteria	A	B	C	D	E	F	G	H	I	J
Range of development pathways	+	+	+	+	0	0	+	–	–	+
Size of application area	–	–	0	–	+	+	–	–	+	0
Availability of standards and implementation guides	–	–	+	–	–	0	+	0	0	0
Provision of submodels	+	+	+	0	–	0	+	0	+	0

– : lowers the applicability of reference architectures within that category
0 : has neither a positive nor negative effect on applicability
+ : increases the applicability

I: Constrained—Layered-based—Enterprise. The meta abstractions of all reference architectures in this category constitute hierarchies. Additionally, there is a large feature overlap when comparing reference architectures. Big Picture organises standards in three dimensions, enterprise levels, lifecycle and value chain. Since Big Picture is based on ISA-95, its dimensions can be completely mapped onto RAMI 4.0 (Megow, 2020; ISO/TR, 2018). IIRA consists of four viewpoints describing business objectives for the system, activities to create intended functionalities, interfaces and interactions, and technologies for the implementation. The functional and business viewpoints of IIRA can be aligned with the layers and lifecycle of RAMI 4.0 (Fraile et al., 2019). I3RM integrates complementary features of RAMI 4.0, IIRA, and SME, thus showing various overlaps with these reference architectures. Besides, while IMSA and KSTEP share the same layers and dimensions with RAMI 4.0, the latter adopts different standards for the lifecycle and telecommunication axis (Han, 2020; Federal Ministry for Economic Affairs and Energy, 2018). SME and SM2 describe the same hierarchy levels and similar layers compared to RAMI 4.0. Finally, ISA-95 is used as the basis for every reference architecture in this category, except for IIRA and I3RM. IIRA's functional viewpoint overlaps with the lower levels of ISA-95, whereas the business viewpoint is only loosely connected to the top level.

J: Concrete—Layered-based—Enterprise. Both reference architectures are hierarchical and service-oriented, and represent the system in three levels, namely edge, plant, and enterprise, each modelling similar features. One major difference is that while IBM Industry 4.0 includes a data storage and analytics service on both the enterprise and plant level, IIRA/Thingsboard separates the storage from analytics functions.

In summary, applying the classification frame of reference results in well separated categories for a large set of reference architectures, because each category contains reference architectures that are comparable to one another. Specifically, the reference architectures for each category share the same meta abstraction and show a significant feature overlap.

4.4. Applicability analysis

By the *applicability of a reference architecture* we mean the capability of a reference architecture to be adopted and applied in practice. To support practitioners in understanding and selecting appropriate reference architectures, we analyse the applicability of reference architectures in each category using the criteria defined in Section 3.4. Although this analysis provides first insights into the applicability of a wide range of reference architectures, more work needs to be done in structuring this analysis, for example, by conducting a systematic implementation comparison, which is beyond the scope of this study. In what follows, the applicability of reference architectures within the categories is qualitatively evaluated. The applicability analysis is summarised in Table 4. Reference architectures which are most applicable can be found in Category C, while category H consists of those that are least applicable. *The variation of applicability of reference architectures within each category is low*, which has also been shown by the validation of the classification in Section 4.3.

The range of development pathways is larger for layered-based topologies since there are more paths from top to bottom, thus leading to more design decisions that need to be made. Consequently, network-based reference architectures are generally more applicable than layered-based ones. This effect is less eminent for reference architectures that only have few layers, such as Shoestring and IBM Industry 4.0, compared to multi-dimensional models, like RAMI 4.0 and IIRA.

Regarding the size of application area, IoT reference architectures in the categories E and F are more applicable than network-based approaches and those focused on the integration of enterprise functions, because the IoT paradigm inherently covers a wider range of applications. Moreover, reference architectures that include a vast number of layers, such as RAMI 4.0 and Big Picture, are capable of representing more features of digital systems compared to smaller reference architectures. Therefore, they enable the design of a larger variety of systems. Conversely, most network-based reference architectures focus on manufacturing control, and would require much effort if designers sought to adopt these for a different application.

Approximately half of classified reference architectures provide standards or some form of implementation guides. Specifically, concrete reference architectures, such as WoT and Shoestring, provide the most implementation and development guidelines, thus reducing the overall number of design decisions significantly. In contrast, layered-based reference architectures with an operational or enterprise focus, such as RAMI 4.0 and ISA-95, seldom include design guidelines but often propose to use a wide range of standards, which facilitates the design process. Besides design guidelines, concrete reference architectures in the categories C, G and J also rely on technology recommendations to support the implementation. For example, Shoestring proposes a service-oriented architecture, whereas the ADACOR/JADE concretisation leverages agents to implement the holonic behaviour.

The provision of submodels, which prescribe certain system features or behavioural characteristics, increase the applicability of reference architectures, since fewer design decision have to be made. Specifically, these submodels or behavioural characteristics provide guidance in the form of design constraints. While many layered-based enterprise reference architectures include various submodels, those based on a network topology are typically constrained by certain behavioural characteristics. For example, ISA-95 contains a submodel for the data flow among resulting digital systems, whereas ADACOR requires the developer to implement the behaviour of an adapting control structure. Conversely, IoT reference architectures in the categories E and F rarely include submodels or specific behavioural characteristics, which yields a lower applicability.

Practitioners can use this applicability analysis as a guide to select a specific reference architecture based on their needs. For example, to build a standalone machine monitoring system, a developer may be interested in a highly applicable reference architecture, since these provide more design guidelines. Additionally, the features of more abstract reference architectures, such as the integration with enterprise functions, are not required to design this standalone system. Therefore, based on Table 4, the reference architectures in classes C and G can be selected since these have the highest level of applicability.

5. Discussion

In this section the findings and limitations of the classification and applicability analysis are discussed. Additionally, we compare the proposed classification approach to previous ones, and describe implications for practitioners and academics in the form of recommendations to increase the applicability of reference architectures.

5.1. Findings

The definitions and characteristics described in this study provide a rough guideline to separate reference architectures from system architectures, frameworks and platforms. However, the boundaries in terms of level of abstraction between those different types of models are not sharp, especially for system architectures and frameworks, which makes a segregation between them difficult. Furthermore, the frame of reference is capable of classifying a wide range of reference architectures despite their varying areas of application and different uses. Additionally, the proposed measures and criteria are appropriate tools for comparing and analysing the applicability of a large number of reference architectures. However, they can only assess the topmost view that describes the key features of a reference architecture.

This study is subject to the following limitations: first, we only focus on reference architectures and do not provide insights into platforms or frameworks for digital manufacturing. Further, due to the wide range of considered models, a deep comparison and alignment is not feasible. Thus, if particular features of a reference architecture are of interest, concentrating on a small subset of models should be preferred. Besides, a more accurate applicability analysis requires a structured implementation comparison and a quantitative evaluation of reference architecture designs, which is beyond the scope of this study.

5.2. Comparison with existing classification and alignment approaches

Compared to previous approaches to classify and align reference architectures, we have proposed a classification frame of reference independent from a particular model or digital manufacturing domain. Similar to Monostori (2014), this study conducts a survey of reference architectures across multiple digital manufacturing domains. While Weyrich and Ebert (2016) classify and compare reference architectures for IoT applications based on the standards they contain, we analyse standards to examine the maturity and applicability of reference architectures. Compared to Bader et al. (2019), who select IoT models based on the number of internet searches, this paper selects models that relate to any of the digital manufacturing paradigms. Although Kassner et al. (2017) differentiate between abstract and concrete models, which is similar to the level of abstraction axis proposed in this paper, their study lacks a clear distinction between the different types of models they discuss. Additionally, multiple approaches classify reference architectures based on common features (Soares et al., 2021; Li et al., 2018; Moghaddam et al., 2018; Kaiser et al., 2022b), whereas this study only performs a feature analysis for validation. In contrast to a functional alignment (Pedone and Mezgár, 2018; Megow, 2020; Pivoto et al., 2021; Fraile et al., 2019; Alliance for Internet of Things Innovation, 2018; Moghaddam et al., 2018; Federal Ministry for Economic Affairs and Energy, 2018; Nakagawa et al., 2021), the development of a feature map (Soares et al., 2020; Guth et al., 2018; Nakagawa et al., 2021), or skeleton models (Han, 2020; Soares et al., 2020), the analysis performed in this study leverages measures and a set of criteria. We acknowledge that these are only capable of a high-level analysis of features and the applicability of reference architectures. However, for a broad literature survey as it was conducted in this study, it is difficult to apply one of the above approaches due to the range and heterogeneity of considered models.

5.3. Implications for practice

There are several implications for practitioners and academics who aim to adopt a reference architecture or develop a new one. Specifically, we provide a *set of recommendations to help increase the applicability of reference architectures* in the digital manufacturing domain. These recommendations are an immediate result from the classification and applicability analysis conducted in this study:

- Domain-specific reference architectures (Industry 4.0, IoT, manufacturing control, CPS) are easier to adopt than more general reference architectures. A successful application of general reference architectures, such as RAMI 4.0, may require additional strategies for a complete system, or developers may only leverage specific features, such as the administration shell, to build system components.
- Reference architectures should be open, that is, they should follow standards and resulting systems should be able to interface with those derived from other reference architectures. Since contemporary information systems consist of various types of components and interfaces, providing interoperability should be a key feature of reference architectures.
- Reference architectures should be joined to cover a larger domain. For example, RAMI 4.0 could be combined with ADACOR to supplement the high level business and operational views with concrete specifications of the system behaviour. Moreover, system design can become simpler using several combined reference architectures and standards instead of a single one that covers all aspects of digital manufacturing, because it requires less effort to divide the design process into subproblems. Additionally, joined reference architectures yield a larger area of application.
- Reference architectures should make use of appropriate technologies and standards to help narrow the range of development pathways. Specifically, abstract and constrained reference architectures can be concretised by making design decisions and developing detailed implementation rules, including specific system characteristics. Conversely, concrete reference architectures become constrained or abstract through not considering development guidelines.

6. Conclusions

This paper set out to compare and analyse reference architectures relevant to digital manufacturing systems. We have reviewed and classified a wide range of models that are referred to as ‘reference architectures’. In particular, we have defined selection criteria that a model (used in system design) needs to satisfy in order to be referred to as a ‘reference architecture’. Additionally, an overview of the different ways people discuss reference architectures in the literature has been provided. The contributions of this study are threefold: first, a clear distinction between reference architectures, system architectures, platforms and frameworks for digital manufacturing is provided. Second, a frame of reference is presented and validated, which allows for the classification of a wide range of reference architectures, and guides practitioners into a reasonably small set of reference architectures to consider. Third, an applicability analysis of reference architectures that belong to the same category is performed.

Compared to previous classification approaches, we have proposed a frame of reference capable of classifying a wide range of reference architectures independent from a particular model or digital manufacturing domain. In contrast to existing alignment and comparison methodologies, this study relies on measures and a set of criteria to compare reference architectures and analyse their applicability.

There are several implications for practitioners. Practitioners should focus on highly applicable reference architectures when aiming to develop systems since these are easier to adopt. Reference architectures achieve a high applicability by being domain-specific, following standards that enable interoperability among systems, and utilising appropriate technologies. Besides, these implications can also be used to increase the applicability of newly created reference architectures.

Due to the wide range of considered models, an in-depth comparison and analysis of reference architectures is not feasible. More insights can be gained from concentrating on a small subset of reference architectures and conducting a structured implementation comparison. Besides, two pathways arise from the proposed metamodelling approach: first, this study concentrates on the reference architecture view within the proposed metamodelling approach. However, little research has been done to compare and analyse system architectures. Specifically, the manner in which platforms and frameworks relate to system architectures requires further investigation. Second, there is a need to analyse how other types of platforms and frameworks relate to the ones focused on digital manufacturing and align these to the proposed metamodelling approach.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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