A Survey and Comparison Analysis of Reference Architectures for the Cloud Computing and Internet-of-things Context

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Abstract— **Increased connectivity and emerging autonomous cloud and Internet-of-things technologies are motivating the transformation of the traditional product-focused development to cloud-based solutions and service-oriented business model in many companies. In line with this, several reference architectures for the cloud computing and Internet-of-things have been developed by various research initiatives and industry vendors. Although some of these reference architectures have continued their development tracks in parallel and have different focus, they also have similarities in many perspectives, which may result in confusion in understanding and applying appropriate reference architectures for specific use cases. The aim and main output of this study is therefore to survey these existing Internet-of-things reference architectures using the research method of systematic mapping study, clarify their characteristics, and analyze in-depth how these reference architectures address various perspectives, including technology, process, quality and key system concerns, business and people. Based on the analysis we discuss motivating factors of the reference architectures, the coverage of business architecture and customer context in the reference architectures, as well as the impacts of the reference architectures to research community and practice. In addition, we present several other relevant activities and initiatives related to the architecture context for cloud computing and Internet-of-things.**

Keywords-reference architecture model; survey; comaprison analysis; industrial internet-of-things; smart industrial automation.

I. INTRODUCTION

This article is an extended version of a conference paper [1] published at ICSEA 2017 (the twelfth International Conference on Software Engineering Advances), one of the IARIA conferences. This article has extended the previously published conference paper with more details on the applied research method and a much more in-depth comparison analysis of the reference architectures.

The German Federal Ministry of Education and Research defines Industrie4.0 [2] as the flexibility to enable machines and plants to adapt their behavior to changing orders and operating conditions through self-optimization and reconfiguration. Consequently, future smart factories require systems to have the ability to perceive information, derive findings and insights, and change their behavior accordingly, and store knowledge gained from experiences. Many organizations start to see the potential opportunities of the Internet-of-things and its impacts on providing solutions that could offer operational advantages [3].

Within EU, Cloud Computing and Internet-of-things are listed as hot topics. The European Commission has outlined a European Cloud Computing Strategy [4], and urged for the need to ensure Europe being at the forefront of the development of Cloud Computing and Internet-of-things to benefit on both demand and supply side through wide-spread cloud use and cloud provision. In line with this, there has been a number of EU-funded research initiatives and activities on Cloud Computing and Internet-of-things, covering various aspects such as communication, hardware technology, identification and network discovery, security, interoperability, standardization, etc. Some examples are IERC – European Research Cluster on the Internet of Things [5], Industrial Internet Consortium [6], Industri4.0 [7], and the creation of the Alliance for Internet of Things Innovation (AIOTI) [8] by the European Commission [9], which initiates the development and future deployment of the Internet-of-things technology in Europe. There has also been a number of EU-funded research activities in Internet-of-things implementation and adoption, addressing various domains and use cases in smart cities, smart energy and smart grid, healthcare, food and water tracking, logistics and retail, and transportation [10].

Successful adoption of cloud computing and Internet-of-things requires guidance around planning and integrating relevant technologies into the existing services and applications. Both industry and academia that want to implement cloud-based solutions seek for more information about best practices for migrating and adopting cloud computing and Internet-of-things concepts. According to [11], "Defining a cloud reference architecture is an essential step towards achieving higher levels of cloud maturity. Cloud reference architecture addresses the concerns of the key stakeholders by defining the architecture capabilities and roadmap aligned with the business goals and architecture vision". Study [12] holds similar viewpoints. According to [12], in order to effectively build cloud-based enterprise solutions, there is a need for the definition of a systematic architecture that provides templates and guidelines and can be used as a reference for the architects or software engineers within the software development lifecycle. Therefore, several reference architectures have been developed and evolved. According to [13], a reference architecture incorporates the vision and strategy for the future. With high level of abstraction, a reference architecture provides a common structure and guidance for dealing with core aspects of developing, using and analyzing systems and solutions that can be tailored to different use cases and specific needs from multiple organizations.

There are several well-known reference architectures for the Internet-of-things that have been developed over the years. Some examples are Reference Architecture Model for Industrie 4.0 (RAMI4.0) [14], Industrial Internet Reference Architecture (IIRA) [15], IoT Architectural Reference Model (IoT-ARM) [16], etc. However, only a subset of the available IoT reference architectures have been reviewed in literature, for instance, study [17] compares two major architectures IoT-ARM and IIRA, whereas study [18] analyzes the IoT architectural reference model (IoT-ARM) and the architecture proposed by WSO2. To our knowledge no detailed survey and analysis of a comprehensive coverage of IoT reference architectures has been published previously to describe the wide spectrum of reference architectures that are available for the cloud computing and Internet-of-things context. The main objective of our research is therefore to systematically select and review published literature, and also include the state-of-the-practice results from various research initiatives and activities within the cloud computing and Internet-of-things area in order to present a holistic overview of the existing reference architectures for the cloud computing and Internet-of-things context.

We have noticed that although some of the reference architectures in this survey have continued their development tracks in parallel and have different focus, they also have similarities in many perspectives, which may result in confusion in understanding and applying appropriate reference architectures for specific use cases. Consequently, we have defined the following research questions:

1) What reference architectures have been reported in the cloud computing and Internet-of-things context?

2) What are the major perspectives covered in these reference architectures?

3) What are the main characteristics for each reference architecture with respect to the different perspectives?

4) What are the impacts of the reference architectures to research community and practice?

In this paper, we present a survey of the existing reference architectures for the Internet-of-things, identify the main perspectives covered in these reference architectures, and analyze the characteristics of these reference architectures from these identified perspectives, such as technology, process, quality and key system concerns, business and people.

The remainder of the paper is structured as follows. Section II describes the research method used for this study. Section III presents an overview of the existing reference architectures for the cloud computing and Internet-of-things. Section IV describes some relevant organized Internet-of-things initiatives and activities. Section V gives an in-depth comparison analysis of the surveyed reference architectures from different perspectives, including technology, process, quality and key system concerns, business and people. Section VI discusses some principle findings of the surveyed reference architectures, including the main motivating factors of the reference architectures, the coverage of business architecture and customer context in the reference architectures, as well as the reference architectures' impacts on research and practice. Section VII concludes the paper.

II. RESEARCH METHOD

The inclusion of the reference architectures in this survey is based on the results from a mapping study [19] as well as additional state-of-the-practice information from various research initiatives and activities within the cloud computing and Internet-of-things area, and covers therefore a collection of the existing reference architectures available. The systematic mapping study is a formalized and repeatable process to document relevant knowledge on a specific subject area for obtaining all available research information related to a research area. The mapping study includes several steps:

(1) definition of research questions;
(2) conduct search for primary studies;
(3) screen papers for relevance using inclusion and exclusion criteria defined; and
(4) classify keywords of abstracts and synthesis of the data extracted. These steps are detailed in [19].

As pointed in [20], the evolution of cloud computing and Internet-of-things has been mainly industry-driven. There are a variety of tools, platforms and infrastructures developed by different business vendors, providing frameworks with various hardware and software capabilities that are used in many industrial cloud-based solutions. Therefore, in addition to searching in scientific databases, we also searched on web sites about different cloud providers, white papers published in industrial communities, such as ARC Advisory Group [21], which performs technology market research for industry. Two major relevant postings from ARC include Operational Technology Viewpoints [22], which provides insights on emerging technologies, practices, and processes for enhancing industrial operations, and Industrial IoT/Industrie 4.0 Viewpoints [23] on digitizing industry and infrastructure.

III. REFERENCE ARCHITECTURES FOR CLOUD OMPUTING AND THE INTERNET OF THINGS

This section summarizes the existing well-known reference architectures for cloud computing and the Internet-of-things.

A. *Reference Architecture Model for Industrie 4.0 (RAMI4.0)*

RAMI 4.0 [14] is a reference architecture for smart factories. It was initiated in Germany, and is driven by major companies in industry sectors. RAMI 4.0 addresses the Industrie4.0 [7] problem space from three dimensions, i.e., it is hierarchically structured to manage both vertical integration within the factory, as well as horizontal integration extending beyond individual factory locations, in combination with lifecycle and value streams of manufacturing applications for all the factories and all the parties involved, from engineering through component suppliers to the customers. This reference architecture aims to address four aspects, including horizontal integration through value networks, vertical integration within a factory, lifecycle management and end-to-end engineering, and human beings orchestrating the value stream. In RAMI4.0, the term Industrie4.0 is used to stand for the fourth industrial revolution in the organization and control of the entire value stream along the life cycle of a product. All relevant information is available in real-time through the networking of all instances, e.g., people, objects and systems involved in value creation. By connecting these instances, the value stream are derived from data at all times to create dynamic, self-organized, cross-organizational, real-time optimized value networks based on a range of criteria, such as costs, availability and consumption of resources.

B. *Industrial Internet Reference Architecture (IIRA)*

IIRA [15] is a standard-based reference architecture developed by the Industrial Internet Consortium [6] for industrial internet systems, which are large end-to-end systems integrating industrial control systems with enterprise systems, business processes and analytics solutions. In this context, the term industrial internet is used to represent Internet-of-things, machines, computers and people, enabling intelligent industrial operations using advanced data analytics for transformational business outcomes. It embodies the convergence of the global industrial ecosystem, advanced computing and manufacturing, pervasive sensing and ubiquitous network connectivity.

This reference architecture is based on ISO/IEC/IEEE 42010:2011 [24] and adopts the general concepts in the specification, such as concern, stakeholder, and viewpoint. The term concern refers to any topic of interest pertaining to the system. The various concerns of an industrial internet system are classified into four viewpoints, i.e., business, usage, functional and implementation. The business viewpoint addresses the concerns of the identification of stakeholders and their business vision, values and objectives. The usage viewpoint addresses the concerns of expected system usage and capabilities. The functional viewpoint focuses on the functional components in an industrial internet system, their interrelation and structure, the interfaces and interactions between them and with external environment. The implementation viewpoint focuses on the technologies needed to implement functional components, communication schemes and lifecycle procedures. Some key system characteristics addressed in IIRA to ensure the core functions of industrial systems over time include safety, security and resilience.

C. *IoT Architectural Reference Model (IoT-ARM)*

IoT-ARM [16], developed within the European project IoT-A, is an architectural reference model that aims to connect vertically closed systems, architectures and application areas for creating open systems and integrated environments and platforms. In this model, Internet-of-things is treated as an umbrella term for interconnected technologies, devices, objects and services. This reference model consists of several sub-models, of which a primary and mandatory model is the IoT domain model, describing all the concepts and their relations that are relevant in the Internet-of-things, such as devices, IoT services, and virtual entities. All the other models, such as the IoT information model, functional model, communication model, IoT trust, security and privacy model, together with the IoT reference architecture are based on the concepts introduced in the domain model. The IoT reference architecture adopts the definition of architectural views and perspectives from [25], though excludes use case specific views to ensure IoT-specific needs and application-independence in the reference architecture. The key architectural views of the Internet-of-things reference architecture include IoT functional view, IoT information view, IoT deployment and operational view. The architectural perspectives of the Internet-of-things reference architecture tackle non-functional requirements, including evolution and interoperability, availability and resilience, trust, security and privacy, and performance and scalability.

D. *IEEE Standard for an Architectural Framework for Internet of Things (P2413)*

The P2413 standard [26] provides an architectural framework that aims to capture the commonalities, interactions and relationships across multiple domains and common architecture elements. It includes descriptions of various Internet-of-things domains, definitions of IoT domain abstractions, and identification of commonalities between different IoT domains. It also provides a blueprint for data abstraction and trust that includes protection, security, privacy, and safety. Similar to the Industrial Internet Reference Architecture, P2413 leverages existing applicable standards and follows the recommendations for architecture descriptions defined in ISO/IEC/IEEE 42010 [24]. According to [26], this standard provides a reference architecture that builds upon the reference model. The reference architecture covers the definition of basic architectural building blocks and their ability to be integrated into multi-tiered systems. The reference architecture also addresses how to document and mitigate architecture divergence. In this standard, things, apps and services can be integrated into what would be abstracted as a “thing”. Information exchange could be horizontal or vertical, or both.

E. *Arrowhead Framework*

The Arrowhead framework [27] was developed within an European research project in automation, which aims to facilitate collaborative automation by networked devices for five business domains, i.e., production (manufacturing, process, and energy), smart buildings and infrastructures, electro-mobility, energy production and virtual markets of energy. This framework is based on service-oriented architecture to enable the Industrial Internet-of-things. The loosely coupled and discovery properties of service-oriented architecture improve the interoperability between devices and the integration of services provided by these devices. The concept of local clouds with well-defined isolation from the open Internet is used to support some key requirements of automation systems, such as real-time, security and safety, scalability and engineering simplicity. The dynamic characteristic of Internet of things is key in this framework. On the one hand, things come and go, and they may have limited bandwidth or energy supply. On the other hand, the integration of IoT systems needs to be dynamic depending on the demand and availability. There are three core components in the local cloud services, i.e., service registry, authorization, and orchestration. In order to be Arrowhead compliant, the applications within the network should register the services they provide within the service registry component. The authorization component manages the access rules for specific services, and the orchestration component manages connection rules for specific services to allow dynamic reconfiguration of the service consumer and service provider endpoints [28].

F. WSO2 IoT Reference Architecture

Based on the projects deployed with customers to support Internet-of-things capabilities, the company WSO2 has proposed a reference architecture [29] that aims to support integration between systems and devices. Their definition of the Internet-of-things is the set of devices and systems that interconnect real-world sensors and actuators to the Internet. The WSO2 reference architecture consists of five layers, including:

(1) device layer, in which each device has a unique identifier and is directly or indirectly attached to the Internet;
(2) communication layer, which supports the connectivity of the devices with multiple protocols for communication between the devices and the cloud;
(3) aggregation/bus layer, which aggregates communications from multiple devices, brokers communications to a specific device, and transform between various protocols;
(4) event processing and analytics layer; which processes and acts upon the events from the bus, and perform data storage; and
(5) client/external communication layer, which enables users to communicate and interact with devices and obtain views into analytics and event processing.

Besides these vertical layers, there are also two cross-cutting layers: (i) device manager, which communicates with and remotely manages devices, and maintain the list of device identities; and (ii) identity and access management for access control.

G. Microsoft Azure IoT Reference Architecture

The Azure Internet-of-things reference architecture [30] is built upon Microsoft Azure platform to connect, store, analyze and operationalize device data to provide deep business insights. This architecture consists of core platforms services and application-level components to facilitate processing needs across three main areas of IoT solutions, i.e., (1) device connectivity; (2) data processing, analytics and management; and (3) presentation and business connectivity. The guiding principles for the architecture include software and hardware heterogeneity to manage diverse scenarios, devices and standards, security and privacy, as well as hyper-scale deployments. The goal of the reference architecture is to connect sensors, devices, and intelligent operations using Microsoft Azure services. The key architecture components to reach this goal include:

(1) device connectivity, which manages different device connectivity options for IoT solutions;
(2) device identity store, which manages all device identity information and allows for device authentication and management;
(3) device registry store, which handles discovery and reference metadata related to provisioned devices;
(4) device provisioning, which allows the system to be aware of the device capabilities and conditions;
(5) device state store, which handles operational data related to the devices;
(6) data flow and stream processing;
(7) solution UX for graphical visualization of device data and analysis results;
(8) App backend, which implements required business logic of an IoT solution;
(9) business systems integration; and
(10) at-rest data analytics.

H. Internet-of-everything Reference Model

The Internet-of-everything reference model [31] is developed by the Architecture Committee of the IoT World Forum hosted by Cisco. This model defines standard terminology and functionality for understanding and developing Internet-of-things solutions, which connect people, process, data and things to enable intelligent interactions between them to achieve relevant and valuable business opportunities. This reference model is composed of seven levels, including:

(1) physical devices and controllers that control multiple devices;
(2) connectivity for reliable and timely information transmission between devices and the network, across networks, and between the network and low-level information processing level;
(3) edge/fog computing that bridges information technology and operational technology, i.e., performing high-volume data analysis and transformation of network data flows into information suitable for storage and higher level processing;
(4) data accumulation that converts event-based data generated by the devices to query-based data consumption for applications to access data when necessary;

(5) data abstraction that renders data and its storage to enable developing simple and performance-enhanced applications;
(6) applications that vary from control application to mobile application or business intelligence and analytics; and
(7) collaboration and processes that involve people and business processes to empower smooth communication and collaboration between people.

I. Intel IoT Platform Reference Architecture

Intel has defined a system architecture specification (SAS), which is a reference architecture for Internet-of-things, i.e., for connecting products and services so that they can be aware of each other and surrounding systems in their ecosystems [32]. There are two versions of reference architectures: version 1.0 for connecting the unconnected, using an Internet-of-Things gateway to securely connect and manage legacy devices that are lack of intelligence and Internet connectivity; version 2.0 for smart and connected things, addressing security and integration capabilities that are essential for real-time and closed-loop control of the data shared between smart things and the cloud. Similar to the Internet-of-things reference architecture proposed by IoT World Forum Architecture Committee, version 2.0 also facilitates the integration of operational technology and information technology. The Intel Internet-of-things reference architecture is a layered architectural framework, comprising of:

(1) communications and connectivity layer, which enables multi-protocol data communication between devices at the edge and between endpoint devices/gateways, the network, and the data center;
(2) data layer with analytics distributed across the cloud, gateways, and smart endpoint devices for optimized time-critical or computation-intensive applications;
(3) management layer for realizing automated discovery and provisioning of endpoint devices;
(4) control layer;
(5) application layer; and
(6) business layer utilizing the application layer to access other layers in the solution.

There is a vertical security layer as well, which handles protection and security management across all layers, spanning endpoint devices, the network, and the cloud.

IV. OTHER INTERNET OF THINGS ACTIVITIES

In addition to the reference architectures presented in the previous section, there are also several other projects, activities and initiatives dedicated in the architecture context for cloud computing and the Internet-of-things, summarized in the following sub-sections.

A. IoT European Research Cluster (IERC)

The objective of IERC initiative [5] is to define a common vision of Internet-of-things technology and address IoT technology research challenges with respect to connected objects, the Web of Things, and the future of the Internet capabilities at the European level, and enable knowledge sharing in the view of global development. According to IERC, Internet-of-things is a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual things have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network. To facilitate the vision of Internet-of-things business ecosystems implementing smart technologies to drive innovation, a wide range of research and application projects have been set up within the IERC initiative, investigating aspects related to (i) devising disruptive business models, transforming traditional business model to data-driven models where all actors in the value chain are closely interconnected; (ii) trust evaluation and management in Internet-of-things, concerning provision of reliable information and maximizing security, privacy and safety; (iii) the impact and consequences of the fast-paced technology development enabling connected things, services, data and people on society with respect to legal considerations, regulations and policies, such as personal data protection, data ownership; (iv) standards and IoT platforms that support open and dynamic interaction across both dimensions of horizontal IoT domains and vertical application domains, and overcome the fragmentation of closed systems, architectures, and applications. A tightly related Internet-of-things activity to IERC is the Alliance for Internet of Things Innovation (AIOTI) [8], which was initiated by the European Commission to address the challenges of Internet-of-things technology and application deployment, including standardization, interoperability and policy issues that are of common interest among various IoT players.

B. Smart Applicances (SMART)

SMART is an EU-funded study [33] with focus on semantic assets for smart appliance interoperability. Smart appliances are devices used in households capable of communicating with each other and being controlled via Internet. It provides a standardized framework for the smart appliances reference ontology, of which recurring concepts can be used and extended in several domains in addition to residential environments.

C. Architecture and Interfaces for Web-oriented Automation System (WOAS)

The project WOAS [34] is funded by the German Federal Ministry of Economics and Technology as an industrial joint research project with ten German automation companies involved. The aim of this project is to research a new architecture for automation systems based on cloud-based web technologies. The proposed architecture is referred to as a Web-Oriented Automation System (WOAS). A WOAS comprises a system kernel and a configurable number of automation services that implement and realize the required automation functions. The automation service is realized according to the concept of I40 component [14]. The connection of the automation service with distributed automation devices in the network is implemented via standard industrial interfaces and is also based on the concept of I40 component.

D. *Reference Architecture for IoT-based Smart Factory*

A research study [35] presents a reference architecture for smart factories and defines the main characteristics of such factories with a focus on sustainable energy management perspective. According to this study, Internet of things relies on both smart objects and smart networks. It is a system in which the physical items are enriched with embedded electronics, such as RFID tags and sensors, and are connected to the Internet. This reference architecture builds upon the interactive relations between smart factories and customers, allowing smart factories to collect and analyze data from products and processes for improved perception of customers' needs and behaviors, as well as better products and services. There are several sets of technologies and perspectives in this reference architecture, including smart machines, smart devices, smart manufacturing processes, smart engineering, manufacturing IT, smart logistics, big data and cloud computing, smart suppliers (i.e., building sustainable relations with suppliers), smart customers' behavior, and smart grid infrastructure for energy management.

V. A COMPARISON ANALYSIS OF THE REFERENCE ARCHITECTURES

The reference architectures described in Section III have certain similarity in technical concepts and architectural principles, but there are also differences in their respective technology approaches and implementations. Therefore, we group particular characteristics that have similar concerns to describe the same or related aspects of these reference architectures. The aspects in the comparison that we have identified and are going to address include:

(1) technology perspective, addressing key concepts and principles used in the reference architecture;
(2) process perspective, addressing the coverage of guidelines and process steps involved when using the reference architecture to generate concrete architectures or migrate existing solutions using the reference architecture;
(3) quality and key system concerns perspective, addressing main quality attributes and system characteristics that a specific reference architecture focuses on; and
(4) business and people perspective, addressing the coverage of value stream aspect and users-centered perspective in a specific reference architecture.

The comparison analysis of the main characteristics of the reference architectures is detailed below, and Table I at the end of the paper summarizes the comparison of the surveyed reference architectures.

A. *Technology*

The transformation of industrial sectors towards digitalization represents a complex problem space that often requires a solution space with multiple viewpoints or dimensions to describe, understand, and manage this complexity. This is reflected in several reference architectures that are often comprised of multiple models (as in e.g., IoT-ARM), multiple viewpoints (as in e.g., IIRA, P2413), or multiple layers (as in e.g., RAMI4.0, WSO2, Azure IoT, Internet-of-everything model, and Intel IoT). In contrast to these architectures, the Arrowhead framework takes another approach that focuses on cloud integration technologies. It applies service-oriented architecture, and builds local and inter cloud with orchestrated services to enable collaborative automation.

The level of standardization and usage of standards are also different among the reference architectures. For instance, IIRA and P2413 follow the architecture descriptions and general concepts such as concern, stakeholder, and viewpoint as defined in ISO/IEC/IEEE 42010. RAMI4.0 follows and extends other standards, i.e., IEC62264 and IEC61512. IoT-ARM adopts the definition of architectural views and perspectives from [25], utilizing viewpoints with respect to function, information, concurrency, development, deployment and operation to describe a system's internal structure, and the context viewpoint to describe a system's external entities.

Among the other reference architectures, a different approach has been taken instead of using a specific standard. A typical approach is the usage of an established architecture style. For example, the arrowhead framework applies service-oriented architecture to handle interoperability at service level. The WSO2 and Azure IoT reference architectures choose multi-layered architectures to handle interoperability issues within communication layer or device layer using specific protocols and technologies.

B. *Process*

Most of the reference architectures provide some guidelines and process steps at different levels of detail on the instantiation of the reference architectures. For instance, RAMI4.0 introduces an administration shell that allows the integration of physical things to Industrie4.0. WSO2 provides a mapping into products and capabilities of the WSO2 platform when instantiating the WSO2 reference architecture. Regarding reference architectures IIRA, Azure IoT, Internet-of-everything, and Intel IoT, they all focus on the integration of information technologies (IT) and operational technologies (OT). IIRA provides an implementation viewpoint that describes the technical representation of an industrial internet system and the technologies and system components required for IT/OT integration. The reference architectures Azure IoT, Internet-of-everything, and Intel IoT can be instantiated into concrete solutions and align with domain-specific designs. The reference architecture IoT-ARM provides very detailed guidelines and engineering practices on how to derive concrete architecture from the reference architecture, which specifies transformation rules for translating the abstract models into a concrete architecture. The reference architecture P2413 aims to capture the commonalities across domains and thus provides a basis for the instantiation of concrete domain-specific architectures.

C. *Quality and key system concerns*

Although the quality attributes addressed in the reference architectures vary, there are a couple of key quality concerns that are common to all, i.e., interoperability and security, which are also two major challenges in the context of cloud computing and Internet-of-things, in which distributed devices and systems from various vendors are connected to exchange data.

Interoperability is defined as "*the capability to exchange information with each other based on common conceptual models and interpretation of information in context*" [15]. Different reference architectures address interoperability differently. For instance, IIRA addresses syntax interoperability in connectivity functional layer, and semantic interoperability in data management. WSO2 uses standard interoperable protocols such as HTTP, MQTT, and AMQP. Similarly, Intel IoT promotes standard-based environment for achieving interoperability. In IoT-ARM, the interoperability is achieved through the design-choice process by identifying and evaluating design choices with respect to their impact to interoperability.

Security is defined as "*the condition of the system operating without allowing unintended or unauthorized access, change or destruction of the system or the data and information it encompasses*" [15]. As for interoperability, various reference architectures address security differently. For instance, IIRA proposes an integrated approach to security by considering end-to-end security capability across all the viewpoints. WSO2 focuses on encryption on devices, identity models, access control, and management of keys and tokens to address security requirements. Intel IoT provides a layered end-to-end security approach for endpoint device, network, and cloud levels. In Azure IoT, security measures are taken across various areas, including device and user identity, authentication and authorization, and data protection, etc.

D. *Business and people*

Interconnecting things, services, and people, and extracting useful information and knowledge from data analysis will enable intelligent industrial operation, generate new revenue opportunities, and lead to innovative business models. Therefore, the business context, values, and people aspects are essential in reference architectures. Some of the reference architectures have defined specific business viewpoint and people-oriented aspect. For instance, the reference architecture IIRA has a business viewpoint to address the concerns of stakeholders and their business vision, values and objectives. The key capabilities identified in the business viewpoint need to be realized through other viewpoints such as usage, functional and implementation viewpoints. In the reference architecture RAMI4.0, a business process layer is defined to ensure the integrity of the functions in the value stream and map the business models and the overall business process. In contrary to IIRA and RAMI4.0, some other reference architectures do not explicitly include the business perspective. Instead, the business aspect is addressed in the IoT architecture generation process, i.e., generation of requirements and transformation of these requirements into a concrete architecture. The reference architecture IoT-ARM is one such example, in which the definition of business goals sets the scope when generating the concrete architecture. The P2413 reference architecture does not explicitly address the business perspective either, though it explicitly addresses the people aspect by identifying the stakeholders who have an interest in a system and documenting their respective concerns. Some other reference architectures provide technical components that enable business value stream generation. For instance, the Internet-of-everything reference model and Intel IoT reference architecture offer business intelligence and data analytics components to enable smart decision making as a value proposition. Not all reference architectures include the business and people perspective, e.g., the Arrowhead framework and the WSO2 reference architecture.

VI. DISCUSSIONS

The reference architectures described in Section III provide an overview of the existing software architecture research and practice. The following sub-sections discuss the motivating factors of the development of these reference architectures, the scope of cloud computing and Internet-of-things reference architectures, as well as the reference architectures' potential impacts on research and practice.

A. *Motivating Factors of IoT Reference Architectures*

From surveying the existing reference architectures for Internet-of-things, we have found out several driving forces of the development of these reference architectures, including:

(1) increasing complexity and size of the systems due to the tremendous amount of connected heterogeneous devices both within and across domains;
(2) increased need for shorter time-to-market and rapid development;
(3) new collaborative solutions that require integrated and coordinated information management to ensure improved effectiveness and optimized production processes or process chains in a single plant or across plants;
(4) increasing need to achieve interoperability and compliance between different devices and systems;
(5) increased focus on optimizing the assets in a single physical plant, as well as optimizing operations across asset types, fleets, customers and partners involved in the cloud computing and Internet-of-things value chain for value co-creation.

Many of the above driving forces are also in line with the identified objectives of reference architectures as described in [13].

B. *Scope of IoT Reference Architectures*

According to [13], a reference architecture should address technical architecture, business architecture and customer context. When surveying the reference architectures, we have found that most of the reference architectures provide technical solutions, design patterns and tactics. However, the business architecture and customer context are often missing. For instance, some commonly used architecture patterns among these surveyed reference architectures include multitier architecture pattern using edge tier, platform tier and enterprise tier, edge-to-cloud architecture pattern, multi-tier data storage architecture pattern, distributed analytics architecture pattern, gateway or edge connectivity and management architecture pattern, etc. However, the aspects of business models and lifecycle considerations in a business architecture are often missing. In the surveyed reference architectures, RAMI4.0 and IIRA are two reference architectures that explicitly include business architecture aspects. A main characteristics of RAMI4.0 is the combination of lifecycle and value stream with a hierarchically structured approach. IIRA explicitly defines business viewpoint to address business vision, value proposition and objectives. Besides the missing emphasis on business architectures, the customer context that addresses the processes and user considerations in the customer enterprises are often missing as well. This indicates a need for further enhancement of the existing reference architectures with business architecture perspective to help customers realize potential value proposition during the process of concretizing the reference architectures.

C. *Impacts on Research and Practice*

One important aspect of a reference architecture is to provide practices and guidance for generating new concrete architectures [13] in order to be able to identify and close any technical gaps for the implementation of potential use cases. Some reference architectures explicitly address this aspect. For instance, in the reference architecture IIRA, the implementation viewpoint explicitly addresses the technical representation, the technologies and system components required to implement the activities and functions required when generating concrete architectures. Another example is the reference architecture IoT-ARM, which provides best practices and guidance for generating concrete architectures from IoT-ARM. It can also be used to devise system roadmaps that lead to minimum changes between two product generations while guaranteeing system capability and features. Another use of the reference architecture is benchmarking during functional components review process. One example is the reference architecture P2413, which supports system benchmarking, safety and security assessment.

For practitioners in industry, the capability to cope with typical characteristics of legacy systems [36] and address legacy issues is often regarded as one important aspect in a reference architecture. Among the surveyed reference architectures, Arrowhead is one example that addresses explicitly the migration of ISA-95 systems [37] to service-based collaborative automation systems in the cloud. For the reference architectures that do not explicitly take the legacy aspect into consideration, there is a need for identification of further extension and improvement opportunities for the future.

VII. CONCLUSION AND FUTURE WORK

In this paper, we have surveyed existing well-known reference architectures, activities and initiatives for the cloud computing and Internet-of-things. To better understand and apply appropriate reference architectures for specific use cases, we have described the main aspects of these reference architectures, and have made an in-depth comparison analysis of these reference architectures from different perspectives, including technology, process, quality and key system concerns, business and people. The main characteristics covered in these perspectives are described, analyzed and compared among the reference architectures in detail.

Based on the description and comparison analysis, we also discuss the driving forces and motivating factors of these reference architectures, the coverage of technical, business architecture and customer context in the reference architectures, and how they address the generation of concrete architectures, as well as the legacy migration perspective. Although it is difficult to find information on examples of solutions or concrete products implementing each architecture described, we believe that our analysis and discussions would assist practitioners in their choice of reference architectures in practice, and in the meanwhile provide input on how to further improve and develop these reference architectures. For future work, we will examine further the reference architectures to analyze possible options of standardization, and analyze these reference architectures' suitability in different business scenarios and concrete case study contexts.

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TABLE I. A COMPARISON OF REFERENCE ARCHITECTURES FOR INTERNET OF THINGS

Reference Architectures	Technology	Process	Quality and Key System Concerns	Business and People
RAMI4.0	A key concept is I4.0 component. Service-oriented and layered architecture. Follow and extend IEC62264 and IEC61512 standards. Permit encapsulation of functionalities. Standards compliant.	Address product lifecycle management dimension, horizontal integration across factories and vertical integration within factory. Allow step by step migration to I4.0 components.	Address security for functionality and data, functional safety and safety measures. The I4.0 component possesses the quality of service properties necessary for specific applications.	Address people orchestrating the value stream, and value stream dimension throughout product lifecycle and across factories.
IIRA	Key concepts include concern, stakeholder, and viewpoint. Based on ISO/IEC/IEEE 42010:2011. Standard-based open architecture.	Integration of information technologies and operational technologies.	Address safety, security, trust and privacy, resilience, integrability, interoperability and composability, connectivity.	Business viewpoint to address business vision, value proposition and objectives.
IoT-ARM	Key concepts include aspect-oriented programming, model-driven engineering, views and perspectives. Evolution and interoperability are the main drivers for the reference model and architecture.	Provide guidelines and process steps on how to generate concrete architectures, perform IoT threat analysis, and derive design choices and tactics based on qualitative requirements.	Address evolution and interoperability, performance and scalability, trust, security, privacy, availability and resilience.	Business goals, cost and benefit analysis are used in the architecture generation process. Specification of an IoT business process model to make use cases IoT-ARM compliant.
P2413	Key concepts include concern, stakeholder, and viewpoint. Based on ISO/IEC/IEEE 42010:2011 standard.	Provide guidelines for cross-domain interaction, documenting and migrating architecture divergence.	Address system interoperability, functional compatibility, protection, security, privacy and safety.	People perspective is reflected in the process of identifying stakeholders and their concerns.
Arrowhead	Key concepts include local cloud, global cloud. Automation cloud integration based on service-oriented architecture. Information centric.	Provide maturity levels of legacy system migration to cloud, engineering tools for development, and test support of cloud automation systems.	Address service interoperability and integrability, security, latency, scalability, dynamic/continuous engineering.	Not explicit
WSO2	Influenced by open-source projects and technologies	Not explicit	Address connectivity and communications, device management, data collection, analysis and actuation, scalability, security, and integration.	Not explicit
Azure IoT	Key principles include heterogeneity, security, hyper-scale deployments, and flexibility. Data concepts include device and data model, data streams, and device interaction.	A vendor-specific solution architecture	Not explicit	Business systems integration layer and solution UX are two architecture components relevant to business and people.
Internet-of-everything	A key concept is edge-ware. Multilevel model for IoT;	Integration of information technologies and operational technologies; enablement of legacy applications.	Address interoperability, security, and legacy compatibility.	Application layer covering business intelligence and analytics. Collaboration and processes layer explicitly involves people and processes.
Intel IoT	Building blocks include things, networks, and cloud.	Integration of information technologies and operational technologies.	Address data and device connectivity, security, and interoperability.	Value proposition by smart decision making based on data analytics.