A Survey and Analysis of Reference Architectures for the Internet-of-things

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***Abstract*—Increased connectivity and emerging autonomous cloud and Internet-of-things (IoT) 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 Internet-of-things have been developed. 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 of this study is therefore to survey these existing Internet-of-things reference architectures, clarify their characteristics, and analyze them from a variety of perspectives, including technology, process, quality and key system concerns, business and people. We also present several other relevant activities and initiatives related to the Internet-of-things.**

Keywords-reference architecture; industrial internet-of-things; smart industry; industrial automation

I. INTRODUCTION

The German Federal Ministry of Education and Research defines Industrie4.0 [1] 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 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 [2]. In line with this, there are several research initiatives and EU-funded research activities on 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 [3], Industrial Internet Consortium [4], Industri4.0 [5], and the creation of the Alliance for Internet of Things Innovation (AIOTI) [6] by the European Commission [7], 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 [8].

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 [9], “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 [10] holds similar viewpoints. According to [10], 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 [11], 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.

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. In this paper, we present a survey of the existing reference architectures for the Internet-of-things, clarify the characteristics of these reference architectures, and analyze them from a variety of perspectives, including technology, process, quality and key system concerns, business and people.

The remainder of the paper is structured as follows. Section II presents an overview of the existing reference architectures for the Internet-of-things. Section III describes some relevant organized Internet-of-things initiatives and activities. Section IV gives a comparison of the surveyed reference architectures from different perspectives, including technology, process, quality and key system concerns,

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business and people, and discusses the findings from this study, and Section V concludes the paper.

II. REFERENCE ARCHITECTURES FOR THE INTERNET OF THINGS

This section presents some well-known reference architectures for the Internet-of-things.

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

RAMI 4.0 [12] 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 [5] 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 [13] is a standard-based reference architecture developed by the Industrial Internet Consortium [4] 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 [14] 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 as 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 [15], 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 [16], 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 [17] 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 [14]. According to [17], 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 [18] 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 based 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 [19].

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 [20] 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, i.e., (i) device layer, in which each device has a unique identifier and is directly or indirectly attached to the Internet; (ii) communication layer, which supports the connectivity of the devices with multiple protocols for communication between the devices and the cloud; (iii) aggregation/bus layer, which aggregates communications from multiple devices, brokers communications to a specific device, and transform between various protocols; (iv) event processing and analytics layer; which processes and acts upon the events from the bus, and perform data storage; and (v) 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 [21] 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 [22] 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

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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 [23]. There are two versions of reference architectures: version 1.0 for connecting the unconnected, using an IoT 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.

III. 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 the Internet-of-things.

A. IoT European Research Cluster (IERC)

The objective of IERC initiative [3] 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 facilitate 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) [6], 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 [24] with focus on semantic assets for smart appliance (i.e., devices used in households capable of communicating with each other and being controlled via Internet) interoperability. 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 [25] 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 [12]. 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 [26] 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

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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, which allow 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.

IV. ANALYSIS AND DISCUSSIONS

The reference architectures described in section II have 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 are going to address include (i) technology perspective, addressing key concepts and principles used; (ii) 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; (iii) quality and key system concerns perspective, addressing main quality attributes and system characteristics that a specific reference architecture focuses on; and (iv) business and people perspective, addressing the coverage of value stream aspect and users-centered perspective in a specific reference architecture. Table I summarizes a comparison of the surveyed reference architectures

The inclusion of the reference architectures in this survey is based on a mapping study [27] and various research initiatives and activities within the Internet-of-things area, and covers therefore a collection of the existing reference architectures available, which is much more complete than the analysis provided in [28], which analyzes only the IoT architectural reference model and the architecture proposed by WSO2.

From surveying the existing reference architectures for Internet-of-things, we have found out several driving forces of the development of these reference architectures, such as (i) increasing complexity and size of the systems due to the tremendous amount of connected heterogeneous devices both within and across domains; (ii) increased need for shorter time-to-market and rapid development; (iii) 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; (iv) increasing need to achieve interoperability and compliance between different devices and systems; (v) 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 Internet-of-things value chain for value co-creation. Many of these driving forces are also in line with the identified objectives of reference architectures as described in [11].

According to [11], reference architectures should address technical architecture, business architecture and customer context. From surveying the reference architectures, we have found that business architecture and customer context are often missing. Most of the architectures provide technical solutions, design patterns and tactics. 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. However, the business models and lifecycle considerations in the business architecture are often missing. In the surveyed architectures, RAMI4.0 and IIRA are two reference architectures that explicitly include business architectures. 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. Similar to business architectures, the customer context that addresses the processes and user considerations in the customer enterprises are often missing as well.

Another important aspect of a reference architecture is to provide practices and guidance for generating new concrete architectures [11]. Some reference architectures explicitly address this issue. For instance, in 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 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 P2413, which supports system benchmarking, safety and security assessment.

For practitioners in industry, coping with typical characteristics of legacy systems [29] and addressing legacy issues is 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 to service-based collaborative automation systems in the cloud.

V. CONCLUSIONS

In this paper, we have surveyed well-known existing reference architectures, activities and initiatives for the Internet-of-things. To better understand and apply appropriate reference architectures for specific use cases, we have made a comparison of these reference architectures from different perspectives, including technology, process, quality and key system concerns, business and people. We also discuss the driving forces of these reference architectures, how they address technical, business and customer context, 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, and in the meanwhile provide input to further improvement of these reference architectures.

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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.

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