Towards a Reference Architecture Model for Industrial Edge Computing

Alexander Willner and Varun Gowtham

Abstract—In the context of the digital transformation of the industry, whole value chains get connected across various application domains; as long as economic, ecologic, or social benefits arise to do so. Under the umbrella of the Industrial Internet of Things (IIoT), traditional Operational Technology (OT) approaches are replaced or at least augmented by Information and Communication Technology (ICT) systems to facilitate this development. To meet industrial requirements, for example, related to privacy, determinism, latency, or autonomy, established Cloud Computing mechanisms are being moved closer to data sources and actuators. Depending on the context, this distributed Cloud Computing paradigm is named Edge Computing or Fog Computing and various challenges have been subject to several publications. However, a proper reference model that describes the multi-dimensional problem space which is being spanned by this paradigm, seems still to be undefined. Such a model should provide orientation, put work in relation and support the identification of current and future research issues. This paper aims to fill this gap with a focus on industrial automation and follows analog models that have been developed for specific domains such as the Smart Grid Architecture Model (SGAM) and the Reference Architecture Model Industrie 4.0 (RAMI4.0). The proposed Reference Architecture Model Edge Computing (RAMEC) identifies 210 views on the Edge Computing paradigm in the manufacturing domain. Future iterations of this model might be used for the classification of relevant research, standardization, and development activities.

Index Terms—Distributed Computing, Cloud Computing, Edge Computing, Fog Computing, IoT, IIoT, Industry 4.0, Smart Manufacturing

INTRODUCTION

To optimize the efficiency, to establish new business models or to enhance sustainability, various value chains are in the process of getting digitally connected using Internet of Things (IoT) technologies. Within industrial domains, the established Operational Technology (OT) is in the process of being augmented or replaced by Information and Communication Technology (ICT). This evolution is sometimes denoted as the Industrial Internet of Things (IIoT). One driving factor is the motivation to operate a converged, more software-based communication infrastructure, built upon open standards, to enhance flexibility and to allow for data-driven business models in the production industries. This does not only reduce costs for operators but also facilitates a shorter time-to-market span for new products.

Specific challenges in this context are requirements related to industrial communication systems. To support determinism, low latency, and autonomy, many technological approaches related to field buses and Industrial Control Systems (ICSs) have been evolved in the last 70 years. A significant milestone was the invention of the Programmable Logic Controller (PLC) in 1968 to easily modify local control loops.

However, programming PLCs did not evolve at the same pace as Internet technologies. Many control systems are still programmed using Statement Lists (STLs), Ladder Diagrams (LDs), or a Structured Control Language (SCL), following the International Electrotechnical Commission (IEC) 61131 standards. Not only do these approaches impose significant limitations to the potential computing capabilities modern endpoints expose, but also younger generations face significant challenges updating existing code. Further, the maintainability, scalability, and modularity of these programs are rudimentary.

To address the latter, the IEC 61499 standards introduce an event-driven distributed system based on the IEC 61131. Further, Programmable Automation Controllers (PACs) enable the use of higher-level instructions in parallel to software-based PLCs for hard real-time control, for example on Industrial PCs (IPCs).

These developments are now being augmented by recent developments from within the ICT domain, more specifically from the fields of network and system management and distributed systems and communication networks respectively. In the 70 years history of computing, we can observe a cyclic alternation between a centralized computing paradigm (1950s: Mainframes; 2000s: Cloud Computing) and a distributed computing paradigm (1980s: Client Server). The current Edge Computing paradigm distributes the Cloud Computing paradigm by moving functionalities again closer to data sources and actuators. This allows for the usage
of Cloud Computing technologies within several critical IoT domains, particularly in industrial use cases. For example, complex applications or federated learning algorithms [kairouz2019advances] can be orchestrated towards Edge nodes to either influence local control loops or to provide valuable data to a Manufacturing Execution System (MES).

However, a review of related work indicated that the multi-dimensional problem space, that the usage of the Edge Computing paradigm in industrial fields of application spans, has not been properly described yet. Therefore, the main contribution of this paper is the presentation of a Reference Architecture Model Edge Computing (RAMEC) for the manufacturing domain. Analog to the Smart Grid Architecture Model (SGAM) [11] and the Reference Architecture Model Industrie 4.0 (RAMI4.0) [2] and in contrast to technical architectures such as Multi-Access Edge Computing (MEC) by the European Telecommunications Standards Institute (ETSI), the RAMEC is supposed to provide orientation and to put activities such as initiatives, standards, publications and implementations into a broader context.

**RELATED WORK**

**Industrial Automation**

To put the work at hand into context, it is important to understand the application domain we are considering, as different use cases entitle distinct requirements. In this paper, we focus on IIoT domains, i.e. the application of IoT technologies in industrial fields of application. More specifically, the automation within discrete manufacturing. The most important concept here is the so-called Automation Pyramid (IEC 62264) that defines the different layers which modern industrial automation is composed of.

Although this pyramid is sometimes differently defined, in its core, it consists of five layers (see the left part of Figure 1). It starts with an Input/Output (I/O) layer that is controlled by PLCs. These PLCs are interconnected via a Supervisory Control and Data Acquisition (SCADA) system with the MES layer. Finally, the overall production and business systems are exchanging information within an Enterprise Resource Planning (ERP) system. It is also important to notice that different layers are concerned with different sizes and time frames of data.

Following the Industry 4.0 vision, this pyramid will be replaced in the long term by the use of Cyber-physical Systems (CPSs) or Cyber-physical Production Systems (CPPSs). Intelligent units, such as Autonomous Guided Vehicles (AGVs), will then interact directly with each other to enable the most flexible production at the lowest costs possible. In this context, the use of an Asset Administration Shell (AAS) is often mentioned, which, in combination with an ”asset”, then represents an intelligent Industry 4.0 component.

To facilitate this transition, new software-based industrial infrastructure technologies are needed to be introduced into the manufacturing domain (see the right part of Figure 1). The boundaries between physical PLC and the classical IPC will further be blurred by the use of edge-based and distributed Virtual Programmable Logic Controllers (vPLCs). For example, based on IEC 61499. To meet requirements related to reliable, low-latency, and deterministic wired communication, the open standards within the Institute of Electrical and Electronics Engineers (IEEE) Time-Sensitive Networking (TSN) group are currently being adopted. For wireless communication, the TSN standards are in the process of being included in the next 3rd Generation Partnership Project (3GPP) release to allow for Ultra-Reliable Low-Latency Communication (URLLC) over 5G networks. Further, instead of only operating a centralized MES, a Management and Orchestration (MANO) system might dynamically install and run applications on Edge nodes close to the data source, and, for example, Artificial Intelligence (AI) based pre-processing and data analytics can be executed locally [6]. A handy example is an Augmented Reality (AR) based Human Machine Interface (HMI), which requires very short communication latencies and places high processing

![Fig. 1. Future technologies within the current Automation Pyramid layers](http://ieee802.org/1/pages/tsn.html)
demands on object recognition.

**Reference Architecture Model Industry 4.0**

To provide orientation and to guide technical discussions in this rather broad context, a reference architecture model is needed. Within the German initiative "Plattform Industrie 4.0" the previously mentioned automation pyramid has not only been extended in 2015 by considering the product and connected world as hierarchy levels following IEC 62624 / 61512 (z-axis: Product, Field Device, Control Device, Station, Work Centers, Enterprise, Connected World), but also they are put into relationships with various layers (y-axis: Asset, Integration, Communication, Information, Functional, Business) and life cycle streams following IEC 62890 (x-axis: Development and Maintenance/usage Type, Production and Maintenance/usage Instance). As a result, the RAMI4.0 model has been published which is depicted in Figure 2. It has also been standardized as German Industrial Standard (DIN) SPEC 91345 and its different aspects have been mapped to the Industrial Internet Reference Architecture (IIRA) developed by the Industrial Internet Consortium (IIC).

**Smart Grid Architecture Model**

The general idea behind the RAMI4.0, however, has been adopted previously. Namely the SGAM model that has been published in 2012 to describe the important aspects relevant to smart energy networks. As shown in Figure 3 various zones (Process, Field, Station, Operation, Enterprise, Market), domains (Generation, Transmission, Distribution, Distributed Energy Ressource (DER), Customer Premise) and interoperability layers (Component, Communication, Information, Function, Business) are put into relationships. Within these intersections, protocols, data models and use cases are classified for a better definition of key areas.

**3D IoT Layered Architecture**

Based on this idea the Alliance for Internet of Things Innovation (AIOTI) has also widened the scope and defined a 3-dimensional IoT layered
architecture in 2018. As shown in Figure 4, this 8x8x8 matrix aims at covering different concepts that interact with IoT use cases. For readability, we have enlarged the axes labels. They can be further identified by their respective alphabetical designation: on the y-axis (bottom to top): Devices (H), Connectivity (G), Edge Computing (F), Storage (E), Abstraction (D), Service (C), Applications (B), People and Processes Layers (A); on the x-axis (left to right): Identifiability (I), Trustworthiness (II), Security (III), Safety (IV), Privacy (V), Connectivity (VI), Resilience (VII), Reliability (VII); and on the z-axis (left to right): Intelligence (a), Availability (b), Dependability (c), Manageability (d), Integrability (e), Scalability (f), Composability (g), Interoperability (h). The third layer within this figure is titled "Edge Computing" which is responsible in analyzing and transforming data elements. As this distributed Cloud Computing paradigm is at the core of the paper at hand, it is worth to shortly review related work concerning this concept.

**Edge Computing**

While, generally speaking, Edge Computing is a distributed architecture that moves storage and computation capabilities closer to data sources and actuators, surprisingly, the term itself has so far eluded a uniform definition. Further, depending on the context and temporal embedding of the source, other terms such as Fog Computing, Mist Computing, or Cloudlets are being used and defined in quite diverse ways as well. In [1] the authors provide further details about the differentiation of these terms.

Peter Levine, in his presentation in 2017, had embedded Edge Computing fairly well, in the bigger context of Distributed Computing. For about 70 years we observe an alternating trend in distributed computer systems. While the first mainframes could already be used centrally in the 1950s and 60s, the trend changed in the 1980s and 90s in favor of distributed client-server systems. One prominent example in this context is the development of Content Delivery Networks (CDNs), in which data is stored and accessed in a distributed manner and closer to where it is needed. After initial research under the umbrella of the distributed Grid Computing paradigm, data and services have again been stored and hosted more and more centrally under the term Cloud Computing, since the beginning of the new millennium. As mentioned before, however, not all data can and should be processed outside of the own administrative domain and outside defined geopolitical boundaries. The reasons for processing data locally or centrally are manifold and mainly relate to the "V’s of Big Data": Volume (growth of data size), Variety (various types of data), and Velocity (increase in speed in which the data must be processed). However, note that, depending on the source, the number of "V’s" might differ between three [14] and nine [10], with various gradations (e.g. Veracity, Validity, Variability, Volatility, Visualization, and Value). In the context of industrial automation, however, further requirements such as latency and determinism are added as well.

Within the literature, one of the first occurrences of the term Edge Computing can be found in 2001, where the authors of [4] briefly described future challenges for microprocessor design. In one of the most cited papers, the authors of [9] highlighted the future challenges in Edge Computing in 2005. Since then, numerous surveys have been published and the rising number of related papers indicates high research interest.

Additionally, Standards Developing Organizations (SDOs) have started to address this issue as well. For example, within ETSI the MEC working group has published over 35 specifications since 2015, with [3] being the latest one, and within the IEC the topic of Edge Intelligence was discussed in [6]. A broader overview, with a focus on sustainability, is given by the authors in [5]. In this paper, an earlier version of the RAMEC model has briefly been described for the first time, however, not to the extent of this publication.

Within this publication, we follow the Edge Computing definition that has been published by the Linux Foundation in August 2019. This definition has widely been adopted within the relevant community, as various organizations and projects have been involved in writing the corresponding glossary:

“The delivery of computing capabilities to the logical extremes of a network in order to improve the performance, operating cost and reliability of applications and services. By shortening the distance between devices and the cloud resources that serve them, and also reducing network hops, edge computing mitigates the
latency and bandwidth constraints of today’s Internet, ushering in new classes of applications. In practical terms, this means distributing new resources and software stacks along the path between today’s centralized data centers and the increasingly large number of devices in the field, concentrated, in particular, but not exclusively, in close proximity to the last mile network, on both the infrastructure and device sides.” [12]

Finally, it is important to note that the Edge Computing paradigm has not only raised interest in the research and standardization context. Due to its potential business impact, several commercial and non-commercial implementations have been developed. Without any claim to completeness, the following examples should provide an initial overview and are subject to change.

Commercial platforms, that actively support and promote the Edge Computing paradigm, among others are SAP Leonardo Edge Computing, Siemens MindSphere Industrial Edge, Microsoft Azure IoT Edge, Amazon Web Services IoT Greengrass, and IBM Watson IoT Platform Edge. At the same time, multiple open source solutions already exist, that can be used, to implement the first projects.

For example, under the roof of the Linux Foundation individual projects are bundled together. These include Akraino Edge Stack, Baetyl, EdgeX-Foundry, Edge Virtualization Engine, Fledge, Home Edge, and the before mentioned Open Glossary of Edge Computing. Analogously, the project FogFlow has been established under the roof of the FIWARE Foundation, and the projects ioFog, Fog05, and BaSyx under the umbrella of the Eclipse Foundation. Within the OpenStack Foundation requirements and use cases are analyzed and a reference architecture is defined within the Edge Computing Group. Further, in the KubeEdge project, the Kubernetes framework is being extended accordingly.

Further examples with a focus on the use of existing (mobile network) infrastructures include MobiledgeX, OpenEdge, Edge Gravity, or the CDNetworks Edge Computing Platform. But also processor-related activities such as LEDGE from the arm-related Linaro project are active in this field. One of the goals is, among others, to achieve extremely low reaction latency (in the range of microseconds). Distributed edge data centers are acting as a backbone for computing capabilities of a local 5G network with CPSs having only limited computation power.

REFERENCE ARCHITECTURE MODEL EDGE COMPUTING

Hierarchy Levels

The brief overview above gives a first indication of the potential problem space to describe the Edge Computing paradigm; i.e. the complexity of the subject at hand, the Edge Computing paradigm, is rather broad and diverse. One reason is that different terminology is being used and individual requirements are formulated in various application domains. Another reason lies in the unspecific definition of the previously mentioned phrase “the logical extremes of a network”. Depending on the use case, the requirements, and the business model, the logical extreme of a network may vary widely.

The data processing does not necessarily have to take place at the topologically outermost extreme. Rather, there is a broad continuum of possible positioning in a network (often denoted as Fog Computing). In Figure 5 this spectrum of feasible distributions is depicted. As outlined in the lower part of the figure, the location of Edge Computing functionality follows the relevant requirements and does not constitute a binary decision. Following the illustration, at least seven different positions can be distinguished, which are briefly explained below.

The Product Edge is located directly on an intelligent product, which was produced for further use, e.g. a smartphone. Another interesting application is the field of Smart Packaging, in which, for example, the GPS coordinates are regularly transmitted for track and trace use cases. The intelligent product, which controls the production process individually when entering the factory, is more visionary.

The term Deep Edge refers to the integration of cloud computing concepts into, for example, the production plants themselves. Together with the intelligent product such as intelligent and autonomous units can interact directly with each other and allow for the most flexible production system possible; up to an individualized lot size of 1 at the cost of a mass product.

The focus of many discussions and most use cases, however, relate to the concept of Gateway Edges. One reason is that expensive industrial assets
have to be used for a long period to optimize the Return on Investment (ROI). From an economic point of view, often machines are not replaced by more modern variants for several decades. In this case, a gateway, that communicates with the devices by wire or wireless, is located nearby the asset; analog to a PLC.

The **Network Edge** goes one step further, in which every node in a network is considered a potential Edge node. For example, each switch can provide sufficient resources, to run smaller applications. Examples include services such as an Intrusion Detection System (IDS) or a Message Queue Telemetry Transport (MQTT) broker.

The **Private Edge** can be put on a level with a Private Cloud. Here the topological edge is defined as the border of the administrative domain, where the own area of influence ends. This is currently within the focus of most of the commercial offerings.

A particularly interesting use case is the **Colocation Edge**, sometimes referred to as Cloudlets. Smaller data centers are arranged topologically in such a way, that certain requirements can be complied with. For this, either existing distributed infrastructures are being used (CDNs, mobile network infrastructures, ...) or investments have to be made into the construction of new infrastructure. In such a setup, both, the economies of scale that apply to Cloud Computing and the technical feasibility for deterministic communication can be combined (e.g. via dedicated paths using Generalized Multi Protocol Label Switching (GMPLS) or wide-area TSN). This allows for offerings, such as real-time control loops in the cloud(let), that would not be impossible otherwise.

**Problem Space**

The positioning of Edge functionalities alone shows, that the Edge Computing paradigm covers a wide field. Even initiatives, articles and surveys often fail to define, what kind of Edge Computing is subject to the discussions. Depending on the classification, very different requirements are placed on software and hardware. Conversely, this means that, while various existing deployment scenarios could be located in one or multiple positions in such a continuum, different use cases pose even more complex requirements and not a single solution can be used in all contexts. This leads to the main observation that orientation is needed to facilitate discussions.

Further, as indicated in the section before, multiple technology layers (such as connectivity, middleware, or applications) have to be considered in the Edge Computing context. Additionally, cross-layer concerns related to use case specific requirements (such as real-time behavior, security, or management) often influence the focus of discussions. Therefore, analog to the reference models RAMI4.0, SGAM, and the AIOTI 3D IoT Lay-
ered Architecture, we introduce the Reference Architecture Model Edge Computing (RAMEC). As shown in Figure 6, it spans a 3-dimensional matrix with 5 concerns, 6 layers, and 7 levels. Overall, this provides 210 different topics of interest within the Edge Computing paradigm. As an example, the highlighted area B. II. 6. relates to real-time applications embedded within a production asset. Another example related to C. III. 2./6., might be a Tensor Processing Unit (TPU) accelerated edge node nearby a production line, that enables quality assurance of the process based on local video stream analytics. Further information that describes the relevant dimensions in more detail follows.

Layers

Technologies, that allow the Edge node to communicate with the outside world (either internally to devices or externally), are located at the connectivity layer. In the industrial context, this includes developments from the 50s (4-20mA current interfaces), the 80s (field bus systems such as PROFIBUS, CANopen or Sercos I/II) and the 2000s (industrial Ethernet systems like PROFINET, EtherCat or EtherNet/IP); as well as but also local sensor-actuator communication technologies like IO-Link. In the wired area, however, standards of the IEEE from the TSN working group are gradually being adopted. At the same time, more and more wireless technologies are moving into the industry. There is currently great interest in so-called 5G campus networks in particular - i.e. private 5G networks in licensed frequency bands. Also, there are suggestions to use Visible Light Communication (VLC) to connect Edge nodes, and for longer distances fiber optic technologies or Low-Power Wide-Area Networks (LPWANs) like Long Range Wide Area Network (LoRaWAN) (unlicensed band) or Narrowband IoT (NB-IoT) (licensed band).

Traditionally, x86-based systems running Microsoft Windows have been widely used in the industry, that have neither been connected to the Internet nor actively updated (every minute of downtime in production costs). With the advent of open standards and broader hardware requirements, it can be observed, that the underlying Silicon architecture becomes more heterogeneous (e.g. the use of ARM, SPARC, or RISC-V based systems) and also Linux derivatives are used as Operating System.

Many current developments can be assigned to the Middleware layer. While power interfaces and field bus systems require their own communication stacks (e.g. the Highway Addressable Remote Transducer (HART) protocol), modern approaches mainly use the TCP/IP or UDP/IP stack of the operating system. Examples for industrial Edge node middleware include the Open Platform Communications Unified Architecture (OPC UA), as well as the Data Distribution Service (DDS), oneM2M, or Web of Things (WoT).

Ultimately, the most important resource is the actual data, which is assigned to the Information layer, and, depending on the context, may represent so-called digital twins. While field buses bring their own data models, in OPC UA an object-oriented data model is used as a basis and under the term "Companion Specifications", currently OPC UA related semantics are defined, to make it easier for machines to communicate with each other. Other approaches like oneM2M or WoT adapt serialization and middleware independent standards, designed in the Semantic Web context over the last 30 years, and enable the definition of distributed data structures based on linked data concepts.

To extract a value from this data, the actual applications are executed in the Application layer. As mentioned at the beginning, this can be any kind of application or network function, for example, software-based PLCs or AI applications; the latter enables intelligent decision making at the edge. This application can interact locally and autonomously
with the environment or even synchronize with Cloud systems. Embedded in a suitable ecosystem, new business models can emerge, similar to current ‘AppStore’ developments.

**Cross-Layer Concerns**

Furthermore, requirements such as security, real-time capability, (AI) acceleration, and management can be addressed differently at different levels, which can have different characteristics depending on the topological position (so-called **Cross-Layer Concerns**).

The **Security** layer includes a variety of technologies, to ensure the safety of an Edge node. Depending on the level, this includes Virtual Private Networks (VPN), Trusted Platform Modules (TPMs), Unikernels, SELinux, a Public Key Infrastructure (PKI), and many other concepts, including blockchains. In particular, in the context of trustworthy Edge Computing, a combination of isolation and slicing approaches with cryptographic measures is needed to allow for distributed secure data processing.

As mentioned before, there are often hard **Real-Time** requirements, in particular, in the discrete manufacturing context. These again have to be addressed differently on all levels and include technologies like 5G, TSN or Real-Time Operating Systems (RTOS) or the use of dedicated microcontrollers.

For the efficient use of neural networks, for example, Edge nodes can be extended in the **Acceleration** layer. This may involve the use of generic Graphics Processing Units (GPU) or Field Programmable Gate Arrays (FPGA), but also the use of a TPU or other commercial AI accelerators. But also, classical extensions like a TCP Offload Engine (TOE) would be located at this cross-layer concern.

The **Virtualization** layer takes into account, that the Edge Computing paradigm is a distributed Cloud Computing paradigm. Hardware is shared with multiple applications, which are themselves executed separately again. That means approaches like Virtual LAN (VLAN), VT-x, LinuX Container (LXC), classical Virtual Machines (VMs), or sandboxing play an important role here.

Finally, Edge nodes are distributed and must be controlled at the **Management** level. This includes the configuration of network paths and Network Slices, updating firmware or the operating system, on-boarding, and the orchestration of applications (e.g. Virtualized Network Functions (VNFs)).

The integration into an IoT platform also takes place at this level. A specific example is a Centralized User Configuration (CUC) system to configure a TSN-based network via a Central Network Controller (CNC), a specific instance of to the Software-Defined Networking (SDN) paradigm, and the Edge nodes via OPC UA using the PubSub TSN Centralized Configuration (PTCC) protocol, which is currently being developed within the IEEE OPC UA PubSub TSN Working Group.

**Example**

Not all of these 210 different topics of interest within the Edge Computing paradigm are relevant in every use case at the same time. To provide some context, there are already real-world application scenarios in the industry. For example, till only a few years ago, steel manufacturers developed new products through extensive tests in their research laboratories. Today, this can be done faster and more efficiently as powerful computer systems take over a large part of the calculations. To efficiently analyze the high volume of generated data, necessary IT capacities are sometimes installed directly on the production sites with the aid of Edge data centers. This additional computing power enables short latency times in data provision as well as uninterrupted data availability and system-wide security. To comply with various security requirements, potential steel containers that hold the IT systems can be equipped with security doors and have detailed monitoring for many relevant parameters, including access control, fire protection and fail-safe operation.

**Conclusions and Future Work**

We have discussed the need for the Edge Computing paradigm in an industrial context, mainly focusing on manufacturing and automation. As the interest in this area rises, the number of related publications, projects, and initiatives continuously grow as well.

At the same time, more and more aspects are covered which have to be taken into consideration when discussing the Edge Computing subject. Unfortunately, a reference model, describing the overall industrial Edge Computing problem space, is
undefined as of yet. Such a reference model would support the classification of current research, could put related work into relation, and might help to identify potential open research and development questions.

Analog to existing reference models that already describe other problem space domains, such as RAMI4.0, SGAM, or the AIOTI 3D IoT Layered Architecture, we have introduced the Reference Architecture Model Edge Computing (RAMEC) to fill this gap for the industrial Edge Computing context. We gave a brief overview of its current state and provided several examples for each dimension. As a result, 210 distinct interdependent fields have been identified.

While this model has been discussed and matured since 2018 with many industry partners and initiatives, its specific characteristics are subject to change slightly. For instance, the introduction of a trusted substrate layer is currently under discussion for enhanced trustworthiness reflection. Finally, as the key success factor for the acceptance of any technology in the industry, is standardization and easy integration into the existing infrastructure, the standardization of the model is planned. For this upcoming work of the international standardization, several SDOs have already been contacted to identify potential next steps. Namely, this includes ETSI, IEEE, IEC, the Standardization Council Industrie 4.0 (SCI4.0), DIN, the Object Management Group (OMG), and the Multi Stakeholder Platform (MSP).

REFERENCES

[1] Paolo Bellavista et al. “Differentiated Service/Data Migration for Edge Services Leveraging Container Characteristics”. In: IEEE Access 7 (Sept. 2019), pp. 139746–139758. DOI: 10.1109/ACCESS.2019.2943848.

[2] Deutsches Institut für Normung. Referenzarchitekturmodell Industrie 4.0 (RAMI4.0). Tech. rep. SPEC 91345. DIN, Apr. 2016.

[3] ETSI. GS MEC 028: Multi-access Edge Computing (MEC); WLAN Information API. Tech. rep. Sophia Antipolis: European Telecommunications Standards Institute (ETSI), June 2020.

[4] P.P. Gelsinger. “Microprocessors for the new millennium: Challenges, opportunities, and new frontiers”. In: IEEE International Solid-State Circuits Conference. Digest of Technical Papers. (ISSCC). IEEE, Feb. 2001, pp. 22–25. DOI: 10.1109/ISSCC.2001.912412.

[5] Andrea Hamm, Alexander Willner, and Ina Schieferdecker. “Edge Computing: A Comprehensive Survey of Current Initiatives and a Roadmap for a Sustainable Edge Computing Development”. In: Proceeding of Wi2020. Potsdam: GITO Verlag, Mar. 2020, pp. 694–709. DOI: 10.30844/wi_2020_g1 - hamm arXiv: [1912.08530].

[6] IEC. Edge Intelligence. Tech. rep. Switzerland: International Electrotechnical Commission (IEC), Sept. 2017, pp. 1–134.
[7] IIC. *Industrial Internet Reference Architecture*. Technical Report Version 1.9. Industrial Internet Consortium (IIC), June 2019, pp. 1–101.

[8] Shi-Wan Lin et al. *Architecture Alignment and Interoperability - An Industrial Internet Consortium and Plattform Industrie 4.0 Joint Whitepaper*. Tech. rep. IIC / PI4.0, Dec. 2018, p. 19.

[9] Pedro Garcia Lopez et al. “Edge-centric Computing: Vision and Challenges”. In: *ACM SIGCOMM Computer Communication Review* 45.5 (Sept. 2005), pp. 37–45. DOI: [10.1145/2831347.2831354](https://doi.org/10.1145/2831347.2831354).

[10] Suhail Sami and Nada Sael. “Extract Five Categories CPIVW from the 9V’s Characteristics of the Big Data”. In: *International Journal of Advanced Computer Science and Applications* 7.3 (Mar. 2016), pp. 254–258. DOI: [10.14569/IJACSA.2016.070337](https://doi.org/10.14569/IJACSA.2016.070337).

[11] Smart Grid Coordination Group. *Smart Grid Reference Architecture*. Tech. rep. CEN-CENELEC-ETSI Smart Grid Coordination Group, Nov. 2012.

[12] The Linux Foundation. *Open Glossary of Edge Computing 2.0*. Aug. 2019.

[13] Ovidiu Vermesan et al. “The Next Generation Internet of Things Hyperconnectivity and Embedded Intelligence at the Edge”. In: *Next Generation Internet of Things. Distributed Intelligence at the Edge and Human Machine-to-Machine Cooperation*. Ed. by Ovidiu Vermesan and Jol Bacquet. River Publishers, Nov. 2018. Chap. 3, pp. 19–102. DOI: [10.13052/rp-9788770220071](https://doi.org/10.13052/rp-9788770220071).

[14] Paul Zikopoulos, Chris Eaton, et al. *Understanding big data: Analytics for enterprise class hadoop and streaming data*. McGraw-Hill Osborne Media, Oct. 2011.