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IoT INTEGRATION IN QUALITY INFRASTRUCTURE 4.0: POTENTIALITIES AND CHALLENGES

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ABSTRACT
The increasing utilization of the Internet of Things (IoT) has the potential to transform the Quality Infrastructure (QI) by encompassing all its fundamental components: metrology, standardization, accreditation, conformity assessment, and market surveillance. The objective of this paper is to analyze the applications, potentialities, and challenges of using IoT within the context of QI 4.0. The research was conducted through an integrative review, and the results indicate that IoT can facilitate the automation of processes, improve the traceability of products and services, and enable the creation of new standards based on real-time data. However, significant challenges such as cybersecurity, data privacy, and device interoperability must be overcome for QI 4.0 to be fully realized.

Keywords: IoT. Quality Infrastructure. Industry 4.0. Innovation. Technology.

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Revista ARACÊ
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INTRODUCTION

Quality Infrastructure (QI) is the system comprising public and private institutions, policies, legal and regulatory frameworks, and practices aimed at supporting and enhancing the quality, safety, and environmental integrity of goods and services, and processes (INetQI, 2018). As a globally encompassing system, QI protects consumers, facilitates the functioning of domestic markets in countries, and ensures the international recognition of its signatories. To achieve this, it relies on various key components, including metrology, standardisation, accreditation, conformity assessment, and market surveillance.

The digitalisation of information has progressed, increasingly embedding innovations into everyday life i.e. new or improved products or processes (or combinations thereof) that differ significantly from the unit's previous products or processes and have been made available to potential users (product) or brought into use by the unit (process) (OECD, 2018). Currently, among the prominent digital innovations are artificial intelligence (AI), robotics, Internet of Things (IoT), autonomous vehicles, 3D printing, nanotechnology, biotechnology, energy storage, machine learning, cloud computing, big data, augmented and virtual reality, digital twins, among others (BRYNJOLFSSON; MCAFEE, 2016).

This ensemble of technologies, whose connectivity with each other and with human agents is enabled by the internet, characterizes the 4th Industrial Revolution. This is a new stage of industrialization, also referred to as Industry 4.0, which distinguishes itself from previous experiences by promoting unprecedented integration between the physical, digital, and biological domains, thereby fostering significant advancements, as well as substantial risks (SCHWAB, 2018).

This phenomenon, characterized by its rapidity, scope, and intensity, has resulted in new demands that necessitate higher quality, efficiency, and sustainability in processes, products, and services to be met (PTB, 2018). These new social and economic requirements have impacted the QI, creating the need for the enhancement of all its components to continue promoting safety and competitiveness without compromising innovation.

By consulting the existing literature, it is possible to note a substantial increase in research and studies exploring the integration of IoT to enhance supply chains and the strengthen the concept of the value chain (SOUZA; ALMEIDA, 2021); (BROWN et al., 2020); (MILICEVIC et al., 2022). However, there is a growing need for more studies and contributions addressing its utilization within the QI, including in relation to the central theme

Revista ARACÊ
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of this article, which aims to analyse the applications, potentialities, and challenges of using IoT in the context of QI 4.0.

IoT comprised of physical devices capable of generating data on a global scale, has emerged as one of the most promising technologies for the cyber-physical systems that characterize Industry 4.0. This is also true for the QI due to its potential to enable the enhancement of all its key components (UNIDO, 2022).

IoT holds a central position in the enhancements necessary for structuring Quality Infrastructure 4.0 (QI 4.0), also referred to as Smart Quality Infrastructure (MILICEVIC et al., 2022), by enabling real-time sharing, integration, interaction, synchronisation, and availability of data. These actions are considered essential for the reliability of the technical services that fall under the purview of QI (HARRISON et al., 2010). Although IoT and QI are already advanced on a global level, in Brazil the process of research and innovation in these areas is still in development. The country faces such as lack of investment, inadequate infrastructure, and the need for professional training to keep pace with emerging technologies. These facts justify the theme addressed in this article.

To achieve the research objective, an integrative review was conducted, which included the analysis of specialised scientific articles, official documents, and practices identified in a governmental institution that integrates QI in the state of São Paulo, Brazil. The institute of Weights and Measures of the State of São Paulo (IPEM-SP) is a public institution with the mission of executing QI activities in São Paulo. The state of São Paulo houses the largest population in Brazil and contributes 32% of the national Gross Domestic Product (GDP). On the national stage, IPEM-SP stands out in QI research; therefore, information from the institute was incorporated into this study to align theory and practice.

CONCEPTS AND PRACTICES

The phases of industrialization are addressed from the perspective of the changes that each phase brought to how people interact, live, and produce the goods and services they consume (UNCTAD; WTO, 2005). The late 18th century witnessed the 1st Industrial Revolution (IR), characterized by mechanical production powered by water and steam, which involved the production of interchangeable parts for maintenance purposes. The 2nd IR, beginning in the last decades of the 19th century, was characterized using electricity and the assembly line, making mass production possible. The use of computers, the internet, automation, and electronic equipment enabled the 3rd IR. The 4th IR, the current

Revista ARACÊ
ISSN: 2358-2472

historical context, is characterized by the promotion of profound and continuous innovations in all areas of knowledge, including QI.

HISTORICAL CONTEXT OF QUALITY INFRASTRUCTURE

The technological foundations that characterize these first three revolutions were fundamental for the emergence and expansion of railways, road infrastructure, urbanization, electrification, telegraph and telephone systems, telecommunications, and the expansion of maritime, air, and land trade. Additionally, there were significant advances in areas such as medicine, chemistry, metallurgy, food, production, oil, and gas.

From a geopolitical perspective, these changes created a global context that, since the 1970s, has come to be known as globalization (FUCHS, 2018). This term has since been used to describe the accelerated and significant changes characterizing the world, encompassing environmental, social, political, and economic aspects.

For industrial production, trade, meeting the demands of various consumer markets, logistics, and transportation to occur on a global scale, metrology (BIPM, 2021), the science of measurement, its applications, and all theoretical and practical aspects of measurement, regardless of measurement uncertainty and field of application, was fundamental. Thus, since the late 19th century, when metrology was effectively adopted by various countries, numerous standards, tests, and certifications have been created, which, over time, have undergone modifications and combinations.

To better understand and coordinate this new scenario, in which, in addition to metrology other areas of knowledge became important, the United Nations Conference on Trade and Development (UNCTAD) and the World Trade Organization (WTO) published a document in 2005 titled "Innovations in Export Strategy: a strategic approach to the quality assurance challenge” (UNCTAD; WTO, 2005).

The main contribution of this document was the introduction of a new concept called Quality Infrastructure (QI), which encompasses the set of public and private institutions involved in the formulation, issuance, and implementation of standards, as well as in conformity assessments that include inspection, testing, certification, metrology, and accreditation, aiming to prevent trade barriers and facilitate technological cooperation.

Although the innovations characterizing the 4th Industrial Revolution have been occurring since the late 20th and early 21st centuries, the year of 2011 is particularly important. At the Hannover fair, universities, research centres, technology companies, and

Revista ARACÊ
ISSN: 2358-2472

the German government announced a new concept called Industry 4.0 with the following characteristics (ARCIDIACONO; PIERONI, 2018).

- Interoperability – Decentralized decision-making by intelligent machines that communicate with each other and with humans.
- Modularity – on-demand production and customization.
- Virtualization – digital replicas that perform simulations, tracking, and monitoring of production processes through sensors.
- Service orientation – use of optimized technologies aimed at solutions. • Real-time operations – data collection and on-time decision making.
- Interaction – the interaction between humans through social media contributes to the generation of big data, which is extended to machines, creating communication networks among them (FUCHS, 2018).

In 2013, the final report titled "Recommendations for implementing the strategic initiative Industrie 4.0 (KAGERMANN; WAHLSTER; HELBIG, 2013), sponsored by the Federal Ministry of Education and Research of Germany, ratified these characteristics through the concept whose essence is the recognition that it is a phase of industrialization in which industrial automation occurs through the connectivity enabled by Cyber-Physical Systems (CPS) and other technologies. These technologies can create interconnections between the physical, digital, and biological worlds to create more integrated, efficient, and secure production systems (SCHWAB, 2018); (FALLER; FELDMÜLLER, 2015).

In Industry 4.0, through the digitalization and integration of value chains, the goal is to decentralize process control and foster collaboration among intelligent devices via interconnections that occur throughout the entire production and logistics chain. This transformation changes the way machines communicate and use the information to optimize production.

For the operations that enable Industry 4.0, also known as the Smart Factory, several technologies stand out, including: CPS, additive manufacturing, AI, machine learning, robotics, Cobots, Big Data, Cloud Computing, IoT, augmented and virtual reality (AR/VR), and Cybersecurity (STATISTA, 2024); (KLINGENBERG et al., 2021); (MUHURI; SHUKLA; ABRAHAM, 2019); (JARA; LADID; SKARMETA, 2014).

In 2018, the United Nations Industrial Development Organization (UNIDO) presented a document titled "Quality Infrastructure: good governance in Quality Policy Design" (UNIDO, 2018), whose applicability was tested with twenty-six countries and three regional

Revista ARACÊ
ISSN: 2358-2472

groups in Africa and Asia. This document aims to alert and provide guidance for countries to develop a robust QI.

According to the document, public policies that enable a solid QI are essential for countries to promote national, regional, and international trade, as well as to ensure environmental sustainability and social well-being. UNIDO also highlights the importance of establishing QI systems that meet international requirements and stimulate industrial development, competitiveness, and innovation, while also ensuring food safety and protecting human and environmental health.

To achieve these objectives, the institution considers that countries must develop based on their specific needs, guiding principles for quality policy grounded (UNIDO, 2018) in coherence, propriety, optimization, sustainability, and inclusion. Additionally, the production of technical guides is classified as essential because they are documents that help identify and describe the main aspects related to governance, institutions, services, companies, and consumers in the context of QI.

The disruption that Industry 4.0 has caused in relation to concepts and practices that permeated the first three industrial revolutions makes them increasingly obsolete. And, since the QI is inseparably linked to industry, there is an urgent need of its foundations to be reviewed and improved as well (BIPM, 2021).

INTERNET OF THINGS

Although initial research on the IoT dates to 1980, it was during the period between 1999 and 2003, based on studies developed at MIT/USA, that interest in IoT expanded. It was an innovative technology offering the possibility of encoding and tracking objects, contributing to accelerating processes, increasing efficiency, and reducing errors in different contexts and areas of knowledge (GBM, 2024).

With advancement of technology, the term “thing” has come to encompass everything in nature that can generate and share data, including living beings of all kinds and even people. Thus, the IoT began to support an open and comprehensive network of entities that, by incorporating and using smart devices connected to the internet, gained the ability to share data and resources, utilize received information to act in response to situations or environmental changes, and, in specific cases, self-organize (LIAO et al., 2018).

IoT networks can be integrated, depending on the situation, by actuators, sensors, connectivity devices, controllers, computers, data storage and processing devices, and user interface devices for data visualization. Furthermore, there is a need for communication technologies such as Wi-fi, Bluetooth, or cellular networks, including 5G signals. The collection, processing and storage of data are structured from embedded systems or cloud computing platforms, where advanced data analysis algorithms and artificial intelligence transform raw information into useful insights (FERGUSON, 2002). These insights can be used to automated decision-making or to inform human users.

IOT: MINDSET AND PRACTICES

Considering the fundamentals that define and characterize IoT, it is evident that it is an indispensable technology, with its contribution stemming from a structure based on connectivity and intelligence (ZHONG, et al., 2017). Its application has the necessary potential to enhance precision and reliability, promoting the efficiency and sustainability of various types of operations (KAMILARIS; PRENAFETA-BOLDÚ, 2018).

The integration of these components enables the creation of advanced solutions that revolutionize various sectors. In Industry 4.0 e.g. IoT facilitates the implementation of smart factories where the production can be monitored and optimized in real-time. Sensors installed in machines can detect anomalies before they become failures, reducing downtime, and increasing operational efficiency (KAMILARIS; PRENAFETA-BOLDÚ, 2018).

IoT has also presented itself as an opportunity to improve QI. For instance, some National Metrology Institutes are adopting IoT for the issuance of Digital Calibration Certificates (DCC), an initiative aimed at ensuring the reliability of sensor data (BIPM, 2021) from providing detailed information on the calibration of devices, along with the identification and authenticity of the data, thereby ensuring its validity for critical applications.

Despite the promising outlook surrounding the use of IoT, there are still challenges to its effective application in QI. One of the most significant factors impacting this situation is the quality of the information generated, considering that currently, a substantial portion of the data is not standardized, making its validation and quantification difficult (MUSTAPÄÄ et al., 2020).

Besides the technological issues, there are specificities in the global context. Brazil e.g. is one of the developing countries that stands out for being the largest economy in South America and 8th largest in the world. However, despite this position, it faces several

Revista ARACÊ
ISSN: 2358-2472

difficulties regarding the implementation of IoT. In this context, challenges include insufficient investments in equipment that incorporates these technologies, lack of standardization and efficient processes, and deficient forms of relationship among companies throughout the production chain. Regarding human resources, issues related to the quality of education and failures in the development of professional and digital skills of the population are highlighted (CNI, 2016).

Regarding the QI, despite the country ranking 17th in the Global Quality Infrastructure Index (GQII) Program (GQII, 2023), it still faces difficulties arising from discontinuity or overlaps in strategies and actions. This is reflected e.g. in the existence of multiple official terms and nomenclatures used to refer to Industry 4.0, including: advanced manufacturing, smart factory, connected industry, smart manufacturing, and neoindustrialization.

To exemplify these challenges, the state of São Paulo within its administrative structure, an organization to deal with issues related to QI called the São Paulo Institute of Weights and Measures (IPEM-SP). This is a state institution, founded in 1967, which also integrates the National System of Metrology, Standardization, and Industrial Quality of Brazil.

Among the services provided by IPEM-SP it is possible highlight: metrological verification; inspection of measuring instruments; inspection of pre-packaged products; inspection of textile products; inspection of products subject to compulsory conformity assessment; inspection and monitoring of vehicles transporting fractionated LPG; and metrological technical support (IPEM, 2023).

It is a set of services aimed at supporting the industrial and commercial economy of São Paulo through a system of inspection and quality control. However, technological advances, high population density, and urbanization have intensified the demand for verification services and legal metrology to ensure accuracy in commercial transactions, maintain market confidence, and protect consumer rights even more.

As part of the strategy to understand and incorporate the innovations brought by IoT and other technologies that characterize Industry 4.0, IPEM-SP, through its Projects and Digital Transformation Office, conducted questionnaires between March and April 2024. The aim was to understand the perception of employees in leadership positions in strategic sectors regarding aspects related to digital transformation and Industry 4.0, focusing on infrastructure, data management, information systems and applications, target audience

Revista ARACÊ
ISSN: 2358-2472

service, people management, and education. The results of this survey (IPEM, 2023) identified, in practice, the potentialities and challenges faced by an organization in the process of transitioning to QI 4.0.

The first finding was that more than 80% of the agents in leadership positions understand the importance of digital transformation and identify a full understanding of the technologies that underpin Industry 4.0 as essential, considering the changes that these innovations are causing in the services provided by the institute. However, they recognize the need to improve their digital competences (VUORIKARI; KLUZER; PUNIE, 2022), both in a broad sense and specifically. This means that in IoT e.g. this improvement would have to address, at a minimum, issues related to hardware (sensors, actuators, or transmitting devices), middleware (data storage and processing), software, and applications (interface and data presentation) (MAJSTOROVIC, et al., 2019).

Regarding technological infrastructure, it was observed that more than 75% employees recognize it as an essential foundation for managing data, information, and knowledge, and that its improvement brings benefits resulting in innovation of internal processes and improvement in serving the different segments that make up the target audience. In this aspect, IoT seen as a technology capable of generating good results considering its ability to collect and serve as a gateway to storage and processing systems for large volumes of data generated by devices in real time.

The enhancement of cybersecurity and protection of sensitive data were also considered important in ensuring the integrity and confidentiality of information by 90% of the professionals. For the technicians of the Institute, actions to implement robust security measures, such as encryption and multifactor authentication, were considered indispensable to protect systems, enable reliable connectivity, and implement advanced networks, such as 5G.

The importance of continuity and improvement of actions to promote an organizational culture that values innovation and technological adaptation was highlighted by over 80% of the participants. In this context, collaboration with other institutions and harmonization with international regulations to which the country is a signatory were also classified as essential for overcoming challenges.

Considering the different stages and contexts being experienced by different countries in the 4th Industrial Revolution (UNIDO, 2018), it is possible to conclude that the reviews of the collaborators on the challenges faced by IPEM-SP correspond, to a greater or lesser extent, to what is observed in the international context. Thus, it is an experience that identifies, from the point of view of professionals working in QI, various aspects related to the applicability, potential, and challenges that permeate the use of technologies, including IoT, in this transition to QI 4.0.

IOT AND QI 4.0: EVOLVING CONNECTIVITY

The digitalization marked the beginning of an era in which institutions operating in QI needed to restructure their internal operations to provide services based on system integration, integrity, and interoperability (BRYNJOLFSSON; MCAFEE, 2016). In the Fourth Industrial Revolution, this scenario became more dynamic due to the increasing demands for connectivity, which became the central aspect of Industry 4.0 and, consequently, QI 4.0 and its components, with a focus on Metrology 4.0, Standardization 4.0, and Accreditation 4.0 (HARMES-LIEDTKE; OTEIZA, 2021).

The IoT is an indispensable technology in cyber-physical manufacturing (FANG, et al., 2023). Therefore, to answer the question – What are the applications, potentialities, and challenges of using IoT in Quality Infrastructure 4.0 context? – integrative review research was conducted, the method, data collection, and results of which are described below.

METHOD

The procedures of this study were based on exploratory research due to the need to obtain more information and familiarity with the theme, making more explicit (VERGARA, 2003). In order to achieve the proposed objective and answer the central research question – What are the applications, potentialities, and challenges of using IoT in the context of Quality Infrastructure 4.0? – an integrative review was adopted as the method (TORRACO, 2005) which is characterized by the comprehensive search, evaluation, extraction, analysis, and synthesis of references on the topic, integrating different types of studies and sources of information, and presenting the results.

The databases selected for this research were IEEE Xplore and Science Direct, motivated by the high relevance and quality of the indexed articles, which are peer-reviewed and often cited in studies on metrology, QI, and IoT. Additionally, these databases provide access to high-impact conference publications, such as the IEEE International Workshop on Metrology for Industry 4.0 & IoT. Although ACM and Scorpus are also

Revista ARACÊ
ISSN: 2358-2472

valuable sources, the decision was made to focus on the aforementioned databases due to the scientific scope of the study.

Table 1: Search parameters

Search terms	("Internet of Things" OR "IoT") AND ("quality infrastructure" OR metrology OR standardization OR accreditation OR "conformity assessment")
Search fields	Title, abstract, and keywords
Databases	IEEE Xplore and ScienceDirect – selected as databases due to their academic relevance, reliability, interdisciplinary approach, and the number of peer-reviewed scientific papers related to the research question.
Type of information	Scientific articles
Time frame	From 2020 to 2024
Geographic area	No restrictions
Language	English
Source type	Journal
Knowledge areas	Computer science; Engineering; Multidisciplinary; Standardization; Metrology; Industrial; IoT.
Inclusion criteria	Full articles published in Journals related to Internet of Things, Quality Infrastructure, Metrology, Standardization, Accreditation, Conformity assessment published in the last 5 (five) years.
Exclusion criteria	Documents not related to the topics of interest; articles not available for full access

The review also included official governments documents; guidelines, recommendations, and reports issued by internationally recognised institutions that contribute to studies and research related to the topics of interest.

The combination of these diverse sources ensured a multidimensional and enriched approach, allowing for the identification of knowledge gaps, the development of new theoretical perspectives, and the proposition of practical recommendations grounded in evidence (SILVA; SPANHOL, 2013). The methodology strengthened the validity and relevance of the presented conclusions, significantly contributing to the advancement of knowledge in the studied area.

DATA COLLECTION

Research results conducted on IEEE Xplore and Sciencedirect bases, according to the parameters presented in Table 1, are show on Table 2.

Revista ARACÊ
ISSN: 2358-2472

Table 2: Results

Description	Results	
	IEEE Xplore	**Science direct**
Total number of documents found	288	67
Distribution per year	2024 (32); 2023 (61); 2022 (61); 2021 (71); 2020 (55)	2024 (11); 2023 (18); 2022 (20); 2021 (9); 2020 (9)
Documents eliminated after reading abstracts	253	51
Documents read in full	35	16
Documents eliminated after full Reading	26	14
Documents validated and incorporated into the article after full Reading	9	2
Main sources	IEEE Internet of Things Journal; IEEE Internet of Things Magazine	Journal of Manufacturing Systems; Journal of Industrial Information Integration

The initial search, guided by the review's search terms, resulted in 355 documents, with 288 from IEEE Xplore and 67 from ScienceDirect, showing varied annual distribution. Following the initial search, the abstracts of each document were read to verify their relevance to the research. During this process, 304 articles were eliminated. Subsequently, the full texts of the remaining articles that met the inclusion criteria were read to ensure the relevance and quality of the articles for the study and to determine their ability to address the research question. After this review, 40 articles were eliminated, leaving 11 articles, as shown in Table 2. There documents were fundamental for analysing the intersections between IoT and components of QI.

ANALYSIS OF THE RESULTS

The collected data were analysed qualitatively, focusing on the intersections between IoT and the components of QI. The results showed that more than 70% of the articles discuss the use of IoT in QI indirectly, meaning they focus on the ways in which this technology is used and intersects with Industry 4.0.

The Table 3 identifies and groups the selected articles considering their intersections with components of QI.

Table 3: Articles, abstracts and intersections

Article	Abstracts and intersections
Metrology	
Fang et al. (2023)	Abstract: It proposes a model for remote calibration of voltage sources using the common view method of GPS, addressing the relationship between voltage, frequency, and time. Intersection: precise and reliable remote calibration via measurement in IoT systems.

Revista ARACÊ
ISSN: 2358-2472

Ziegler (2020)	Abstract: Review on digital twins highlighting the importance of a universal reference framework. Intersection: the use of digital twins, integrating IoT for precision and efficiency.
Normalization	
Pivoto et al. (2021)	Abstract: Review of Cyber-Physical Systems (CPS) architectures for industrial IoT applications. Intersection: Reviews CPS architectures for industrial IoT applications essential for precision and efficiency in Industry 4.0
Sharma et al. (2022)	Abstract: Analysis of AI standardization, highlighting the need for greater international contribution. Intersection: Highlights the need for standardization in AI, which integrates with IoT systems, aiding in accreditation and compliance assessment.
Lee et al. (2021)	Abstract: Analysis of interoperability and security standards in IoT. Intersection: Need for interoperability and security.
Accreditation	
Karie et al. (2021)	Abstract: Reviews data collection approaches and standardization in smart manufacturing. Intersection: Data collection and process standardization in smart manufacturing, integrating IoT.
Minani et al. (2024)	Abstract: Evaluates security standards and frameworks for IoTbased smart environments. Intersection: security standards for IoT-based smart environments, crucial for reliability and safety.
Conformity Evaluation	
Arzo et al. (2021)	Abstract: Discusses tools and challenges in testing IoT systems. Intersection: Testing IoT systems to ensure devices meet quality standards.
Schlemitz & Mezhuyev (2024)	Abstract: Study on IoT systems testing in industry, emphasizing integration testing. Intersection: ensuring devices and systems are of high quality and secure
Market Surveillance	
Minani et al. (2024)	Abstract: Research on data release technology and location monitoring in IoT-based sensor networks. Intersection: Data and location monitoring in IoT sensor networks, crucial for accuracy and security.
Lin (2021)	Abstract: Review of network automation for IoT, focusing on automation challenges and opportunities. Intersection: IoT network automation, crucial for efficient and secure system operation.

The results indicate that the use of IoT in QI 4.0 is primarily addressed as a technology capable of ensuring the precision, efficiency, and credibility required by the components of QI. Other studies relate to connectivity, which, as a central characteristic of IoT, is ensured by a network that includes the internet; actuators; sensors that collect environmental and operational data; Wi-fi and 5G technologies that ensure efficient data transmission. These data are then processed and transformed into actionable insights through AI. Security measures also play a prominent role in ensuring continuous reliability and compliance.

DISCUSSION

The research highlights the importance of IoT for QI 4.0 by identifying its capacity to promote disruptive innovations and enhance process efficiency. An example is the study on remote calibration of voltage sources using the GPS common view method (FANG, et al., 2023), which demonstrates how IoT can automate and increase precision in metrology.

Revista
ARACÊ
ISSN: 2358-2472

Additionally, the analysis of standardization in AI (ZIEGLER, 2020) reaffirms the need for robust standards to ensure security and ethics in the use of the technology, a fundamental aspect for trust and effectiveness in metrological operations.

Cyber-physical systems (CPS), which combine computing, networking, and physical processes, are essential for automation and control in various sectors (PIVOTO, et al., 2021). The integration of digital twins (SHARMA, et al., 2022), which virtually replicate physical entities for operations optimization, is an example of CPS that illustrates the need for emerging technologies to develop data-driven standards vital for metrology and conformity assessment. Interoperability and security are also fundamental pillars, as highlighted in the review of existing standards in IoT (LEE, et al., 2021), ensuring secure and efficient communication between devices.

The need for security in IoT-based smart environments is reinforced by reviews of standards and frameworks (KARIE; YANG; KEBANDLE, 2021), while systematic analysis of IoT (MINANI, et al., 2024) identifies the need for integrated security frameworks to protect sensitive data. Research on data release and location monitoring technology (ARZO, et al., 2021) explores how sensor integration and distributed computing can enhance efficiency and accuracy in data collection and processing. This advancement is complemented by the use of robust data science approaches (SCHLEMITZ; MEZHUYEV, 2024), essential for handling the complexity and variability of data.

Studies on IoT systems in industry (MINANI, et al., 2024) demonstrate the effectiveness of combined testing to ensure the functionality and security of devices, which can also contribute to market surveillance. The discussion on network automation for IoT (LIN, 2021) highlighted the reduction of complexity and the increase in operational efficiency as main benefits.

This set of aspects closely aligns with the perspective of the Physikalisch-Technische Bundesanstalt (PTB), which asserts that the digital transformation of metrology in Germany should emphasize the digital transformation of metrological services; metrology in the analysis of large volume of data; metrology of communication systems for digitalization; and metrology for simulations and virtual measuring instruments (PTB, 2018).

Among the initiatives that recognise the challenges identified in the articles and seek solutions related to data, security, standardisation, conformity assessment, and aspects within the QI context is the European Metrology Cloud (THIEL, et al., 2017). This initiative by the European Association of National Metrology Institutes aims to create a collaborative platform where National Metrology Institutes, governments, industries, and other interested parties in the European Union's QI context will have the opportunity to enhance their measurement systems through interoperability, support industrial innovation, modernise metrological infrastructures, conduct tests, provide calibration services, issue certificates, promote traceability, and exercise market surveillance through digitalisation.

The analysis of the articles and the intersections with the QI components, along with the previous discussion on each study, enabled addressing the research question: What are the applications, potentialities, and challenges of using IoT in the context of Quality Infrastructure 4.0? The review analysis identified the challenges and potentialities in the context of each selected study.

Among the potentialities, the following stand out: (i) Enhanced accuracy and efficiency – through remote calibration, digital twins, and CPS architectures (FANG, et al., 2023); (ZIEGLER, 2020); (PIVOTO, et al., 2021); (ii) Improved standards and security – through AI standardisation, interoperability, and security frameworks (SHARMA, et al., 2022); (LEE, et al., 2021); (MINANI, et al., 2024); (iii) Reliable data management – via standardised data collection, monitoring, and network automation (KARIE; YANG; KEBANDLE, 2021); (MINANI, et al., 2024); (LIN, 2021).

On the other hand, the challenges are characterised by: (i) Technical and regulatory obstacles: for standardisation, interoperability, and security (SHARMA, et al., 2022); (LEE, et al., 2021); (ii) Complexity of integration: in diverse and evolving IoT environments (ARZO, et al., 2021); (SCHLEMITZ; MEZHUYEV, 2024); (PIVOTO, et al., 2021); (iii) Ensuring privacy and accuracy: in data monitoring and automation processes (KARIE; YANG; KEBANDLE, 2021); (MINANI, et al., 2024); (MINANI, et al., 2024).

Despite the methodological rigor that underprint this research, it is important to acknowledge the limitations of the reviewed studies. Many articles analyse specific cases that may not reflect the diversity of IoT applications in QI across different sectors. Furthermore, the rapid evolution of IoT technology may render some findings quickly obsolete. The review also was limited to articles published in English, excluding potentially relevant research in other languages.

For future research, it is suggested to investigate standards and protocols for IoT integration in QI, focusing on interoperability between different devices and systems. Furthermore, an in-depth study of the impacts of IoT on the quality and conformity of products and services, analysing diverse sectors and mapping areas needing improvement to ensure full integration of these technologies, is recommended.

CONCLUSION

The IoT is an essential technology for the consolidation of QI 4.0 because it enables the improvement of precision, efficiency, and automation of all its components through different applications. However, the effective implementation of IoT in QI faces considerable challenges, including the need for data standardization, cybersecurity, and the development of norms and assessment criteria. Additionally, the training of professionals and the creation of a culture of innovation are considered essential to overcome resistance to change and ensure the successful adoption of these technologies. Thus, IoT can play a crucial role in the evolution towards Quality Infrastructure 4.0, but it requires careful and coordinated integration to reach full potential.

Revista ARACÊ
ISSN: 2358-2472

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