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Review

Emerging Industrial Internet of Things Open-Source Platforms and Applications in Diverse Sectors

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Abstract: Revolutionary advances in technology have been seen in many industries, with the IIoT being a prime example. The IIoT creates a network of interconnected devices, allowing smooth communication and interoperability in industrial settings. This not only boosts efficiency, productivity, and safety but also provides transformative solutions for various sectors. This research looks into open-source IIoT and edge platforms that are applicable to a range of applications with the aim of finding and developing high-potential solutions. It highlights the effect of open-source IIoT and edge computing platforms on traditional IIoT applications, showing how these platforms make development and deployment processes easier. Popular open-source IIoT platforms include DeviceHive and Thingsboard, while EdgeX Foundry is a key platform for edge computing, allowing IIoT applications to be deployed closer to data sources, thus reducing latency and conserving bandwidth. This study seeks to identify potential future domains for the implementation of IIoT solutions using these open-source platforms. Additionally, each sector is evaluated based on various criteria, such as development requirement analyses, market demand projections, the examination of leading companies and emerging startups in each domain, and the application of the International Patent Classification (IPC) scheme for in-depth sector analysis.

Keywords: business intelligence; data analytics; business management; international patent classification; Industrial Internet of Things (IIoT); open-source platforms; emerging applications; industry sectors; market trends; smart technologies

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1. Introduction

The Industrial Internet of Things (IIoT) is a technology that is revolutionizing many industries. It allows devices, machines, and people to communicate and work together in industrial settings, leading to improved efficiency, productivity, and safety. This paper explores different IIoT areas in various sectors and regions to develop potential solutions. The aim is to identify markets or technology areas that are emerging but not yet dominated by large companies or well-funded startups [1–3].

Highlighting the importance of open-source IIoT and edge computing platforms, this work discusses how these innovations facilitate the development and deployment of IIoT solutions. These platforms make it easier to create and deploy IIoT solutions by providing accessible and cost-effective tools for a variety of applications. Popular open-source IIoT platforms include Eclipse Kura, Apache, and Grafana, while edge computing platforms such as EdgeX Foundry and OpenRemote help deploy IIoT applications nearer to data sources, thus reducing latency and bandwidth usage [4–6].

This study aims to discover potential areas where IIoT solutions can be applied, including open-source IIoT and edge computing platforms. The surveyed IIoT solutions can either tackle existing problems or provide new ones with improved features. The evaluation of each area will be based on a range of criteria, such as development requirement analysis, the estimation of market size/demand, the analysis of major companies and startups in each sector, and the utilization of the International Patent Classification (IPC) scheme for sector analysis [7].

To uncover the most promising IIoT solution areas, a comprehensive analysis of both qualitative and quantitative research on IIoT solutions and market trends was undertaken. The study addressed critical questions regarding the technological requirements in different sectors, the current market trends in IIoT, and the identification of sectors where large corporations and heavily funded startups have not yet established dominance.

The study addresses the following question: What are the high-potential, state-of-the-art IIoT solution areas? To answer this, a qualitative and quantitative analysis of research papers on IIoT solutions and trend analysis were conducted [8–10]. This involved addressing three questions: What are the technological requirements in different sectors for IIoT solutions? What are the current trends and developments of IIoT in the market? What sectors and IIoT solutions are not yet dominated by large corporations and heavily funded startups? The outcome of this research was intended to determine the general requirements of the IIoT, as well as the specific requirements of the sector. This would enable research to develop IIoT solutions that either solve an existing problem or introduce a new solution with better features. Each area was evaluated based on different criteria, such as market size, market demand, the analysis of leading companies and startups, patents from companies or individuals, and the valuation of these patents.

In this investigation, we provide thorough know-how concerning the needs of the IIoT market and the particular requirements of each sector. We also identify markets and areas of technology solutions that are emerging and not yet dominated by large companies and well-funded startups. The following sections include background information on IIoT solutions, IIoT communication protocols, business intelligence, business strategy and IT, and task technology theory to accept solutions. Related research is also discussed, as well as the research approach. Examples of IIoT solutions are given for each sector, and a selection of articles is analyzed to determine the main requirements for the implementation of IIoT in different sectors. The results are then discussed, followed by a discussion and an outline of future work.

2. Background

2.1. Internet of Things

The concept of the IoT was introduced with the use of RFID [11]. Subsequently, researchers associated the IoT with other technologies such as smartphones, cameras, and other sensors. A widely accepted definition of the IoT is an internet-connected network of devices that utilizes standard protocols to exchange and communicate information in order to make intelligent decisions, recognize smart decisions, position, monitor, and manage [12]. In other words, the integration of devices such as sensors, actuators, RFID tags, and communication technologies forms the basis of the IoT and enables a variety of objects to be connected to the internet, allowing them to collaborate in order to achieve their objectives [13].

2.2. Emerging Trends in IIoT Architectures

In recent years, the IIoT has seen a significant transformation, with a strong emphasis on creating and applying practical designs known as service-oriented architectures. These architectural solutions aim to construct and deploy IoT infrastructures in industrial settings in a highly effective manner, with the potential to enhance efficiency, productivity, and safety across several industries. Various recommendations and frameworks have emerged, elaborating on the principles of service-oriented architectures in the IIoT field. Two notable instances of these are the IIRA and stratified IoT architectures. These frameworks provide structured guidelines and implementation of IIoT systems. An essential aspect of this phenomenon is the widespread utilization of open-source software and hardware, together with platforms, to fully leverage the potential of IIoT systems.

To improve readers' understanding of this emerging trend, we recognize the following recent publications that extensively examine the complexity of IIoT designs. The initial study focused on the creation of a system that gathers and oversees data from PEM hydrogen producers utilizing the IIoT [14]. This research conducted a comprehensive analysis of data collection and monitoring systems specifically developed for PEM hydrogen generators, which have a vital function in various industrial operations. Users can retrieve this up-to-the-minute data via a web-based interface made possible through an IIoT framework [14]. The impetus for this study stemmed from the necessity of monitoring the production of hydrogen in a photovoltaic (PV)-powered microgrid, in line with the notion of "green hydrogen" generated from renewable energy sources. The paper's contributions encompass real-time monitoring, configuration adaptability, online remote access, the effective implementation of IIoT technologies, and validation through empirical findings. This work satisfies a research need in the field of hydrogen generation by developing and monitoring DAQ systems. It specifically focuses on an IIoT-based approach, which adds value to the existing literature on this issue [14].

The second work discusses the difficulties and technology involved in IIoT designs (SOA2). This work provides significant insights into the primary challenges and emerging technologies in IIoT architectures. It provides a thorough and inclusive evaluation of the topic. The introduction provides an overview of the shift from the IoT to the IIoT, highlighting the IIoT's significance in improving operational efficiency and integrating Information Technology (IT) and Operational Technology (OT). Furthermore, it emphasizes the importance of Industry 4.0 and Cyber-Physical Systems (CPSs) within the framework of the fourth industrial revolution. The process of converting industrial processes into a digital form poses novel difficulties for the complete integration of IIoT systems. In order to tackle these difficulties, the study examines and contrasts three extensively acknowledged IIoT reference architectures: RAMI 4.0 [15] and IIRA [16]. Reference architectures serve as a guide for building IIoT systems, facilitating the incorporation of sensors into enterprise management functionalities [17].

2.3. IoT Communication Protocols

The importance of communication protocols in the development and utilization of IoT solutions is undeniable. Different sectors and industries have distinct requirements, and the selection of an appropriate communication protocol can address these specific needs. The primary focus of Wireless IoT is the utilization of various communication technologies and protocols to link up smart devices. All of these are short-range protocols [18]. In addition, LoRa is a protocol that offers two-way and long-distance communication. Tables 1 and 2 list various communication protocols and their main characteristics, as well as the behavior of different metrics.

Table 1. Comparative analysis of communication protocols in IoT and edge computing.

Feature	Zigbee [19]	RFID [11]	BLE [20]	6LoWPAN [21]	NFC [22]
Governing standard	IEEE802.15.4 [19]	RFID technology [11]	IEEE802.15.1 [20]	IEEE 802.15.4 [21]	ISO/IEC 14443 [22]
Operational frequency	2.4 GHz	Multiple (125 kHz, 13.56 MHz, 902–928 MHz)	2.4 GHz	Various (868 MHz in EU, 915 MHz in USA, 2.4 GHz Globally)	Multiple (125 kHz, 13.56 MHz, 860 MHz)
Network type	Wireless personal area	Proximity-based	WPAN	WPAN	Peer-to-peer (P2P)
Network topology	Multiple	P2P	Star-bus network	Star and mesh	P2P
Power consumption	30 mA, low power	Ultra-low	30 mA, low power	Low (1–2-year battery life)	50 mA, very low

Table 1. *Cont.*

Feature	Zigbee [19]	RFID [11]	BLE [20]	6LoWPAN [21]	NFC [22]
Data transmission rate	250 kbps	Up to 4 Mbps	1 Mbps	250 kbps	106, 212, or 424 kbps
Communication range	Short (10–100 m)	Short (up to 200 m)	Short (15–30 m)	Short (10–100 m)	Very short (0–10 cm, up to 1 m)
Security protocols	AES encryption	RC4 encryption	E0 stream, AES-128	AES encryption	RSA, AES encryption
Signal spreading technique	Direct-Sequence Spread Spectrum (DSSS)	DSSS	Frequency-Hopping Spread Spectrum (FHSS)	DSSS	Global System for Mobile Communications (GSMA)
Key features	Mesh networking capability	Cost-effective	Low power consumption	Widely utilized for internal access	Enhanced security
Primary applications	Home automation and monitoring	Tracking, inventory management	Wireless audio devices	Internet-based monitoring and control	Contactless payments, access control

Table 2. Overview of standard protocols in IoT-edge communication.

Attribute	LoRa [23]	SigFox [24]	Z-Wave [25]	Cellular Networks [26]
Governing standards	LoRa Alliance Specifications	SigFox Protocol	Z-Wave Standard	Various (GSM/GPRS/EDGE, UMTS/HSPA, LTE)
Frequency bands utilized	Multiple (915 MHz in Americas, 923 MHz in Asia)	Varied (868 MHz in EU, 902 MHz in USA)	868–908 MHz	Standard cellular frequencies
Type of network	Long-Range Wide-Area Network (LoRaWAN)	Low-Power Wide-Area Network (LPWAN)	Wireless Personal Area Network (WPAN)	Wide Area Network (WAN)
Network topology	Star	Star	Mesh	Not applicable
Energy consumption	Low	10–100 mW	2.5 mA, low consumption	Relatively high
Data transmission speed	27 kbps	Up to 100 bps (Uplink), 600 bps (downlink)	40 kbps	Not specified
Operational rrange	Up to 5 km	Urban: Up to 10 km; rural: up to 50 km	Indoors: 30 m; outdoors: 100 m	Extensive, several kilometers
Security Features	AES encryption	Basic security measures	AES-128 encryption	RC4 encryption
Signal spreading method	Not specified	Direct-Sequence Spread Spectrum (DSSS)	Not applicable	DSSS
Distinctive characteristics	Long range, energy-efficient	Extended battery life, cost-effective	Simplified protocol	Extended range capabilities
Primary use cases	Smart city infrastructure	Street lighting, energy metering	Home monitoring and control	Machine-to-machine communication

2.4. Business Intelligence

The notion of business intelligence (BI) was initially presented in 1989. It is a Decision Support System (DDS) that is based on data and integrates data collection, storage, and knowledge management with analysis to give direction to decision-making [3]. BI focuses on the analysis of large amounts of data related to a company and its operations, as well as including competitive intelligence as a subset. It allows companies to monitor market trends and other useful data that can help them prioritize areas of interest and high potential. A business intelligence (BI) system is capable of gathering data from multiple sources, which could be related to different business areas, like marketing, production, various business activities, and finance [3]. These data are then transformed and studied using various methods, including reporting, visualization, and data mining.

2.5. Business Strategy and IT Alignment

In the contemporary business world, technology progressions, consolidations and acquisitions, corporate undertakings, regulatory alterations, and strategic alliances create a highly volatile atmosphere. For organizations to thrive in this kind of atmosphere, an efficient and effective IT solution that bolsters both business strategies and procedures is essential [27]. The emphasis of many IT solution providers and IT-adopting companies has shifted to the synchronization of business requirements and IT capabilities. Organizations are now requiring information systems that are better aligned with their business processes and strategies. This has led to an increased demand for such systems. To confront this difficulty, a variety of IT planning and system development approaches have been created, including Business Systems Planning (BSP) [28] and Information Systems Study and Information Engineering [29]. Alignment can be broadly described as the degree to which IT applications, infrastructure, and organizational bodies enable and shape business processes and strategies, as well as the techniques or approaches used to attain a certain level of alignment [30]. Alignment is a key factor in the decision to implement one solution over another.

2.6. Task Technology Fit Theory

Task technology fit is a significant factor to take into account when assessing the approval of an IoT. It offers a method to evaluate the efficiency of technology in a system by examining the connection between technology and the tasks it is meant to facilitate [31]. In an organization, technology can be employed to generate value by enhancing and facilitating individual or collective tasks. However, it necessitates a great deal of effort and resources to put into practice and utilize the various technologies. The inquiry is as follows: How much value does technology bring to an organization [32]? It is difficult to calculate the worth of technology because of the complex links between technology, users, tasks, systems, and processes. Task technology fit (TTF) is a widely used measure that has been suggested to assess the impact of technology [33]. There are various versions of the model, but the fundamental model is composed of task characteristics, technology characteristics, and performance effects. Figure 1 shows the model.

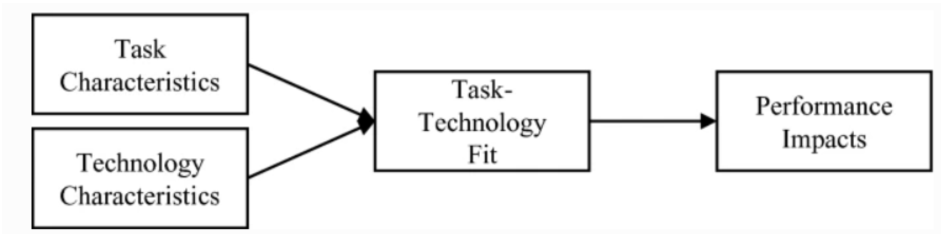

Figure 1. Task technology fit basic model.

2.7. Existing IoT Research Efforts

The IoT has experienced a surge in popularity in the last two decades, as consumers, businesses, and governments have come to appreciate the advantages of connecting these devices to the internet [4]. This has caused organizations that are embracing IoT solutions to concentrate on understanding how this technology can be incorporated into their existing business processes and infrastructure [34].

In 2018, Adai et al. [35] conducted a study to investigate the factors that influence the acceptance and utilization of IoT solutions by a customer named Jordan. The research was intended to fill gaps related to the acceptance of IoT services and develop a model of factors determining consumers' acceptance of IoT technology. The findings suggest that behavioral intention has a significant effect on the user behavior of IoT solutions, and IT knowledge is the most important factor that affects behavioral intention among other factors.

Jangwon et al. [36] explored the role of technology trends in analyzing big data by utilizing patent data and machine learning. Their proposed method can be used to evaluate a target organization and devise strategies for their patented inventions. The research employed Cooperative Patent Classification (CPC) as the classification scheme of patents. Soohyeon et al. [37] also used IPC and CPC to analyze trends for applicants. This research proposed a model that includes four steps: data collection, preprocessing, the extraction of common patterns, and the analysis of the invention trends of applicants. The study identified common invention patterns and extracted the representative technical fields of applicants, and it compared and examined the technical invention trends among each group of applicants.

In 2016, Suwon et al. [38] conducted research that used a multi-criteria approach to identify "killer" IoT applications in Korea. The authors applied an Analytic Hierarchy Approach

(AHP) to analyze a complex decision-making process. They proposed that technology, market, and regulation are the three forces that have traditionally been studied as the determinants of diffusion and the performance of innovative products and services. The technological aspect is highly dependent on practicality, reliability, cost efficiency, and standardization. The market potential is highly dependent on demand, user acceptance, business models of corporations, and an ecosystem-building environment. As for the regulatory environment, industry regulation, consumer protection regulation, and governmental support are the main contributing factors. The results of this paper suggest that market potential is perceived as the most significant factor when assessing the viability of IoT applications, with ecosystem building and business models being the most important factors [38].

3. IIoT Requirement Analysis

A range of technical solutions have been suggested for the purpose of implementing the IoT. Since the potential user base for this technology is extensive and varied, users have different needs that engineers and software developers must be able to meet through a thorough requirements engineering (RE) phase [39]. Therefore, it is essential to create a baseline that can be used as a foundation for the development of any IoT solution in the applicable sectors. This will assist us in addressing the initial research question specified in Section 1.

3.1. Generic IIoT Requirements

An examination of multiple research papers revealed that there are certain IoT requirements that are shared across different industries. These requirements include the management of data generated via devices [40], the necessity of interoperability and open standards to enable seamless communication and data transmission among devices [40–43], the importance of data visualization to create digital representations of physical-world information [42], the need for high-quality sensors and hardware for long-term and sustainable use [44], real-time capabilities for concurrent data communication to facilitate quick decision-making [40–42,45], user-friendly systems for ease of use [41,44,46], the precise monitoring of resources and processes [45], and the reduction in manual data-processing to enhance accuracy and task efficiency [45].

Furthermore, security and privacy aspects play a critical role in IoT requirements. These encompass authentication mechanisms to ensure the legitimacy of accessing entities, data integrity to prevent information alteration during transmission, data confidentiality to safeguard sensitive data from leakage, ensuring availability for uninterrupted system access, false tolerance measures, access control to manage resource access, and system resilience. These requirements collectively form the foundation for successful IoT implementations across diverse industrial domains [40,45,47,48].

3.2. Application Sector Specific Requirements

3.2.1. Industry 4.0

Organizations can use the design principles of Industry 4.0 to decide which components should be part of their initial projects. The requirements that stem from the design principles of Industry 4.0 are the following: the capacity of interconnected systems to make independent decisions without the need for a central system [42]; the capability of systems to act as a service to organizations, rather than a product [42]; and the potential to make dynamic changes by adding or replacing certain components [42]. These are all features of decentralization, service orientation, and modularity, respectively.

3.2.2. Agriculture

In the agriculture sector, specific requirements have been identified, including the need to monitor agricultural production and the measurement of factors that influence crop and livestock growth [47]. Additionally, ensuring reliable access to the web is essential in this context [44]. The monitoring of the food supply chain and the ability to track wasted resources and use data for improvement purposes are also critical aspects of agriculture-sector requirements [47].

3.2.3. Healthcare

In the healthcare industry, several important needs have been highlighted. These include the necessity of a scalable architecture capable of handling a large number of patients while considering constraints such as computer resources, memory, and energy consumption [40,48]. A modular design of solutions is also crucial to allow for the reuse of platforms in various healthcare contexts [40]. Moreover, data freshness is a key consideration, ensuring that no outdated messages are transmitted within healthcare systems [48]. These requirements play a vital role in addressing the unique challenges and demands of the healthcare sector.

3.2.4. Smart Cities

The requirements for smart cities include the ability to scale in order to manage the vast amounts of data from the IoT [41], the capacity to be heterogeneous in order to accept data from multiple sources [41], the capability to self-configure for systems in smart homes [46], the potential to be extended to increase the functions and configurations of connected devices [46], and the intelligence to predict human behavior in various scenarios [46].

3.2.5. Logistics

The logistics sector necessitates the use of instruments to keep up with the ever-changing trends due to the emergence of new tools and platforms [49]. Additionally, it is important to recognize consumer behavior patterns [47]. Security and privacy are also paramount, and the hardware-based root of trust is necessary to guarantee security at the hardware level [49].

4. Open-Source Edge IoT platforms

This section outlines requirements for leveraging open-source edge IoT software platforms (Figure 2). Edge computing for the IoT is a technology that brings certain computational and data analysis capabilities near the origin of data. Edge computing allows certain processes to take place in the most suitable spot, resulting in more secure, dependable, and scalable IoT deployments. By utilizing connected IoT devices or gateways, IoT deployments that use edge computing can benefit from features such as device integration, data ingestion, data-processing, analytics, and device management. The edge is a key factor in the success of IoT. Therefore, the leading vendors of IoT platforms offer edge capabilities. This survey will also investigate the needs of edge computing systems.

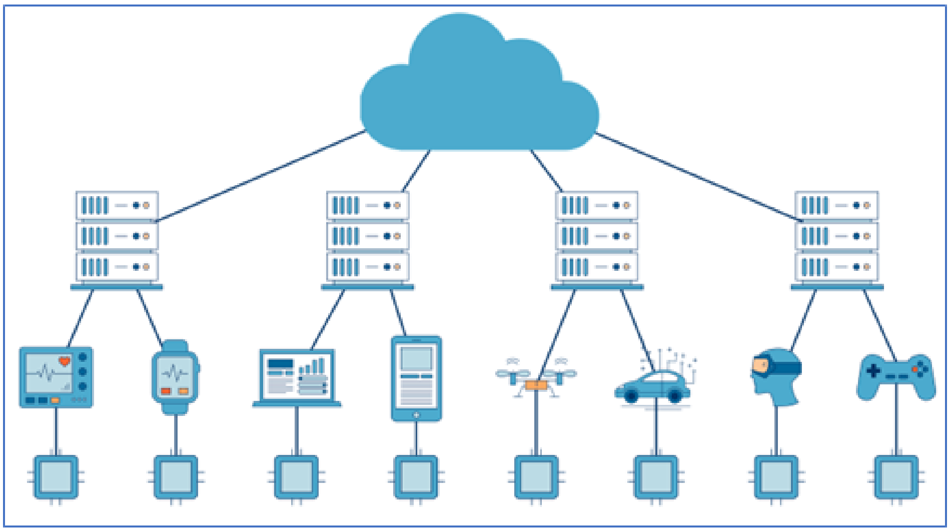

Figure 2. IoT edge network [50].

Open-source IoT platforms are an essential part of the IoT ecosystem, as they provide the connection between device sensors and data networks. In this section, a list of open-source IoT platforms, including open-source databases, is reviewed. These platforms provide the necessary tools and resources to develop and deploy IoT applications. They include open-source software, databases, and cloud-based solutions that enable users to create, manage, and monitor connected devices.

4.1. Overview of Open-Source Databases

These systems are publicly available for data storage and management. They are characterized by their public accessibility and collaborative development. These databases, curated by a collective of contributors, are valued for their versatility, pliability, and cost-efficiency. They are available in different varieties, each designed to meet unique requirements for managing data: Relational databases provide organized storage in tables, exemplified in MySQL, PostgreSQL, and MariaDB. NoSQL databases, such as MongoDB and Cassandra, offer adaptable and unstructured storage for diverse and intricate data types. In-memory databases, such as Redis and Memcached, facilitate rapid data retrieval by storing data directly in the computer's memory. Graph databases, such as Neo4j and ArangoDB, excel at managing data in a graph structure, making them well suited for interconnected data points. Prominent examples available in the market include MySQL, PostgreSQL, MongoDB, and Redis. Each offers distinct characteristics that are well suited to different applications.

4.1.1. Examples

MySQL is a popular open-source RDBMS that is utilized for internet use cases [51]. It is regarded as one of the most widely used, and it globally boasts a substantial community of developers and users. It has the capability to be seamlessly incorporated with a range of computer languages, including PHP, Java, and Python, hence facilitating the development of applications employing these languages [51]. MySQL adheres to ACID principles, ensuring integrity and reliability [51]. MySQL is compatible with multiple platforms such as Linux, Windows, and macOS, allowing for flexible deployment choices [51]. MySQL enjoys extensive support and boasts a substantial community of developers, offering a plethora of tools and assistance. MySQL exhibits exceptional scalability, enabling it to effortlessly manage substantial amounts of data and accommodate heavy traffic loads. Configuring and managing MySQL can be difficult, especially for deployments on a large scale. MySQL does not possess certain sophisticated capabilities, such as built-in support for JSON and functionality for graph databases.

PostgreSQL, or Postgres, is an open-source RDBMS renowned for its sophisticated capabilities and strong adherence to SQL standards [52]. PostgreSQL is a robust and versatile database management system that offers a broad range of data types and extensive functionalities. Configuring and managing PostgreSQL, especially for large-scale deployments, can be intricate. MongoDB offers exceptional performance and scalability, enabling horizontal scaling through the distribution of data across several servers [53]. MongoDB offers automated sharding and replication, simplifying the process of scaling and ensuring continuous availability. The MongoDB Change Data Capture (CDC) function is an essential component that allows for capturing real-time changes, hence boosting the overall capabilities of the system.

Redis is a freely available, memory-based data storage system that operates on a key-value model [54,55]. It can serve as a database, cache, or message broker. Redis lacks the capability to handle intricate queries similar to those supported through conventional SQL databases. Efficient operation of Redis, especially in large-scale deployments, may necessitate additional resources [54,55]. Apache Cassandra is a freely available distributed NoSQL database specifically engineered to provide exceptional availability, scalability, and performance [56]. This technology is especially well suited to applications that necessitate rapid processing and the retrieval of vast quantities of data. Apache Cassandra is a decentralized database that can efficiently manage enormous volumes of data across numerous nodes. The system offers a versatile data model that accommodates various data structures such as wide columns, documents, and key-value pairs [56]. Apache Cassandra provides robustness and resilience by employing a masterless architecture, enabling the uninterrupted operation of nodes even in the event of node failures.

MariaDB is a widely used open-source RDBMS that was specifically built to be compatible with MySQL. The system offers assistance for a range of query types, encompassing SELECT, INSERT, UPDATE, and DELETE statements [57]. InfluxDB offers exceptional performance and scalability, enabling developers to efficiently manage extensive datasets in real time. InfluxDB's capability may be constrained in comparison to other database systems due to its specialized design for time-series data [58]. Due to its emphasis on high-precision timestamps, this database system may necessitate a greater allocation of resources in comparison to other systems. Elasticsearch's emphasis on real-time search and analytics may necessitate a higher allocation of resources compared to other database systems.Elasticsearch's capability may be constrained in comparison to other database systems, as it is purposefully tailored to search and analytics purposes [59].

Apache offers exceptional performance and scalability, enabling developers to efficiently manage extensive datasets in real time. CouchDB is a freely available and open-source database system, allowing users to modify and enhance its source code. CouchDB's emphasis on document-oriented data storage and retrieval may necessitate greater resource allocation compared to other database systems [60].

4.1.2. Comparison

Table 3 lists summaries and compares the open-source databases' diverse architectures that are suitable for various applications.

Table 3. Comparison of popular open-source databases.

Database	Functionality	Flexibility	Pros	Cons
MySQL [51]	ACID-compliant, wide range of data types	Deployable on various platforms	Cost-effective, scalable	Limited advanced features
PostgreSQL [52]	Wide range of data types, advanced features	Integrates with multiple languages	Powerful, flexible	Complex for large-scale deployments
MongoDB [53]	Dynamic queries, JSON-like documents	Suitable for various applications	Highly available, flexible modeling	Requires strong data consistency
Redis [54,55]	In-memory key-value store, supports transactions	Used as database, cache, message broker	High performance, low latency	Not for large data storage
Apache Cassandra [56]	Distributed database, supports wide column	Suitable for real-time analytics, e-commerce	High availability, fault tolerance	Steep learning curve
MariaDB [57]	Compatible with MySQL, various query types	Deployable on-premise, in cloud	Excellent security features	Compatibility issues with MySQL-specific apps
InfluxDB [58]	Time-series data, high-precision timestamps	Monitoring, analytics, IoT	Optimized for time-series data	Limited compared to other databases
Elasticsearch [59]	Full-text search, real-time analytics	Search, analytics, logging, monitoring	Real-time performance, scalability	Resource-intensive for real-time analytics
Apache CouchDB [60]	Document-oriented format, RESTful HTTP API	Web, mobile applications, CMS	Flexible, scalable	Steeper learning curve
Neo4j [61]	Graph data model, Cypher query language	Recommendation engines, network management	Performance for graph data	Limited compared to traditional databases

4.2. Thingsboard IoT Edge Framework

ThingsBoard serves as a comprehensive platform for collecting, analyzing, visualizing, and overseeing data, supporting key IoT protocols including CoAP, OPC-UA, MQTT, and HTTP. It offers flexible deployment options, either cloud-based or on-premises [62,63]. The platform facilitates the creation of workflows triggered by various events, including life cycle changes, REST API activities, and RPC requests [62]. Additionally, ThingsBoard Edge offers an edge computing solution, allowing for data-processing and management directly at the data's origin. This edge solution can integrate with various ThingsBoard cloud services tailored to specific user needs, but it is limited to single-tenant use, prohibiting multi-tenant applications and device-sharing across tenants.

Moreover, ThingsBoard (as shown in Figure 3) boasts a robust, scalable, and fault-resistant infrastructure alongside a secure environment for seamless device management. It can process and standardize input from devices, trigger alarms for various telemetry issues, and support customizable rules for targeted functionalities. It is also capable of managing millions of devices simultaneously without a single point of failure, thanks to its clustered architecture in which each node is independent. Moreover, it offers multi-tenant capabilities beyond the core cluster setup and provides a rich selection of over thirty customizable dashboard widgets for enhanced user interaction.

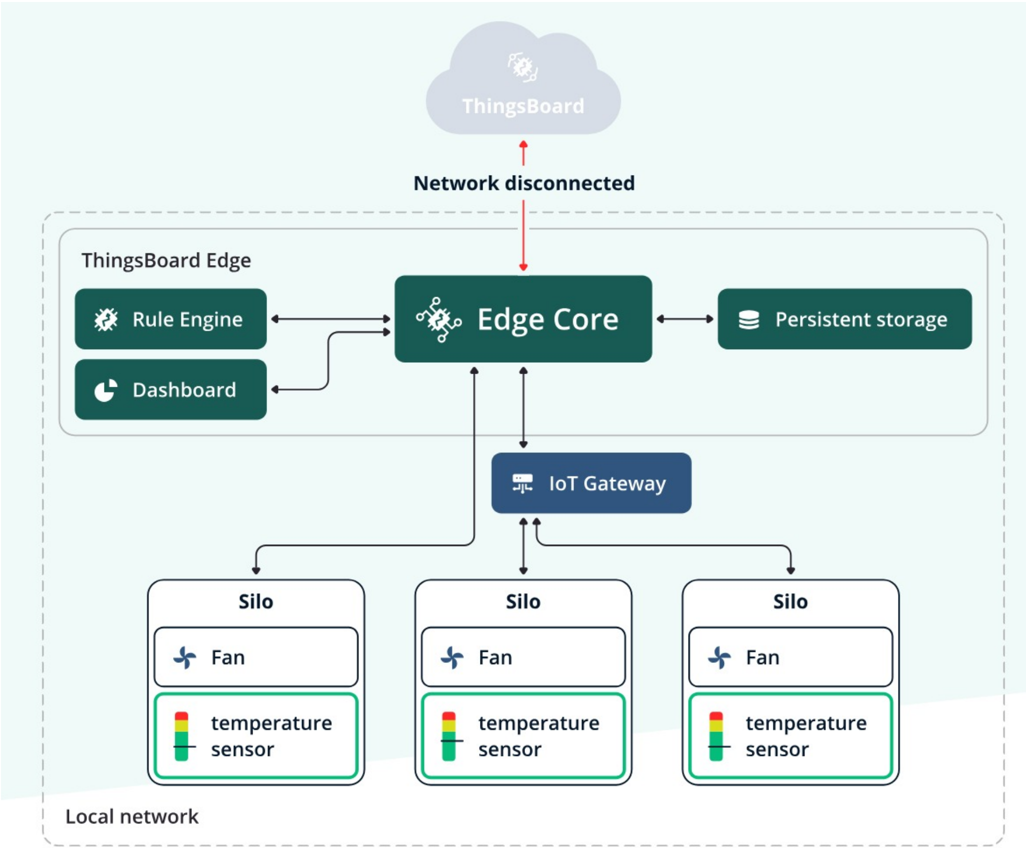

Figure 3. ThingsBoard IoT edge platform [62].

Figure 4 illustrates the support for federated connectivity protocols for data ingestion in the Thingsboard Edge IoT technology. This technology requires an edge platform that is compatible with a wide range of devices and hardware vendors. There are many different standards employed in Internet of Things (IoT) applications, including a large number of accepted ones and a long list of proprietary ones used in both custom-made and pre-made products. Thingsboard edge/IoT platforms are designed to accommodate a broad range of IoT devices with a variety of protocols for data ingestion. These platforms offer a wide range of protocols that can be employed without any extra setup. Popular protocols for edge platforms include multiprotocol platforms for sensor connectivity, such as HTTP, REST endpoints, MQTT, Zwave, BLE, LoRaWAN, ZigBee, and Modbus-TCP.

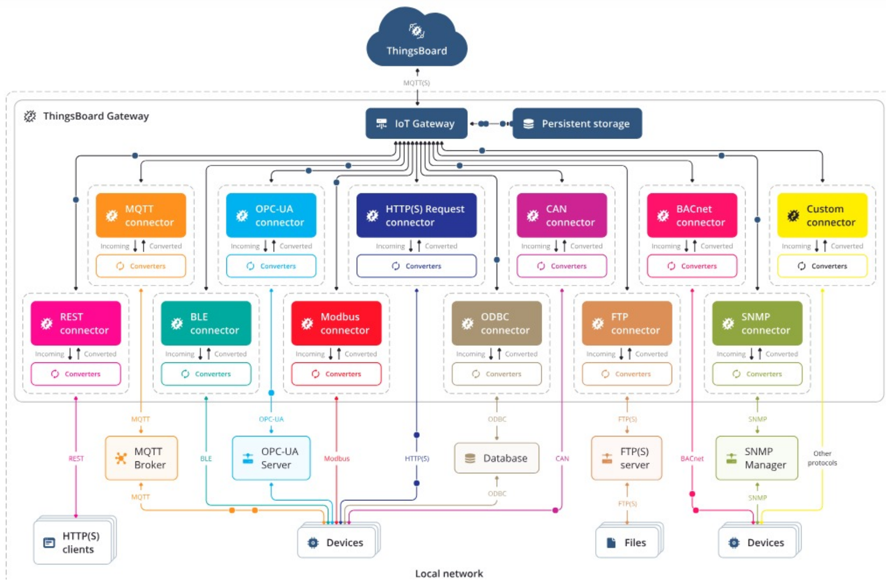

Figure 4. Federated IoT framework [62].

4.3. OpenRemote Edge and Server

OpenRemote has introduced a pioneering open-source platform tailored to developing advanced energy management applications within the IoT domain [6]. This platform is equipped with a versatile asset and attribute framework that accommodates various asset types (Figure 5). It employs protocol agents, including HTTP REST and MQTT, for integrating IoT devices, gateways, and data services. Additionally, the platform features a Flow editor for data manipulation alongside event-driven rule creation capabilities using WHEN-THEN logic and a Groovy UI. A standard Dashboard is incorporated for the provisioning, automation, control, and monitoring of applications. It also offers Web UI components for crafting bespoke project applications, as well as Android and iOS consoles for leveraging mobile services like geofences and push notifications. Moreover, an Edge Gateway solution is available to connect multiple instances to a central management system, complemented with a scalable multi-realms multi-tenant architecture that includes account management and identity services.

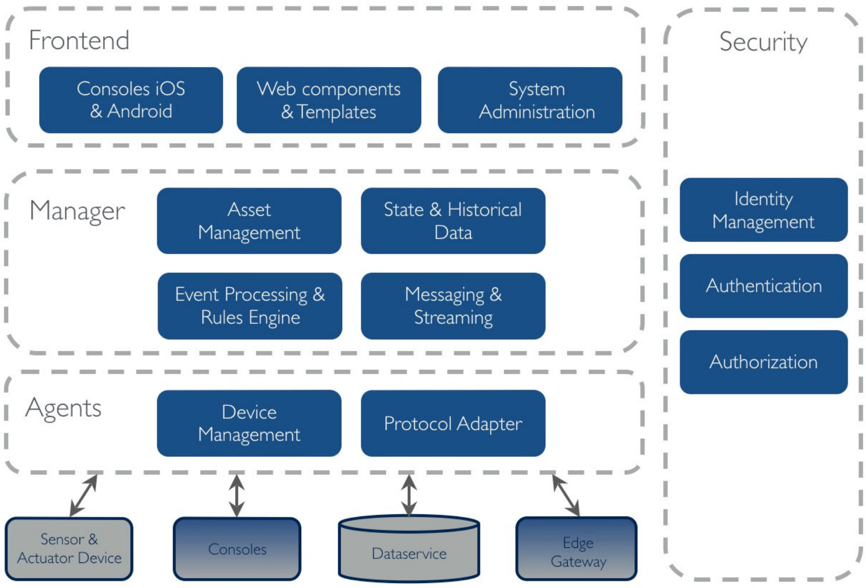

Figure 5. OpenRemote [6].

OpenRemote (Figure 5) has an Edge Gateway feature, which is a manager that connects to another OpenRemote Manager (referred to as the central manager). This is used in scenarios where a manager is needed within a LAN without being exposed to the internet, often running on limited hardware. The edge gateway establishes a connection to the central manager using the Websocket API. To do this, the edge gateway must be provisioned in the central manager to generate client credentials, which can then be used for authentication. Each edge gateway connection is defined per edge gateway realm, and only one connection can be made to a central manager per realm. A PostgreSQL database stores data. The openremote postgresql data docker volume stores PostgreSQL. To create a backup of the installation, we need to make a copy of the volume.

4.4. DeviceHive

DeviceHive is a microservice-based system designed for highly scalable and reliable performance. It can handle large quantities of time series data, such as sensor data, and it provides the scalability necessary to ensure the safety and availability of data [64]. DeviceHive is open-source and can be used for both private and commercial purposes Figure 6). It offers features such as deployment with Kubernetes options, highly granular scalability, persistent database storage, and a hybrid approach (Relational and NoSQL).

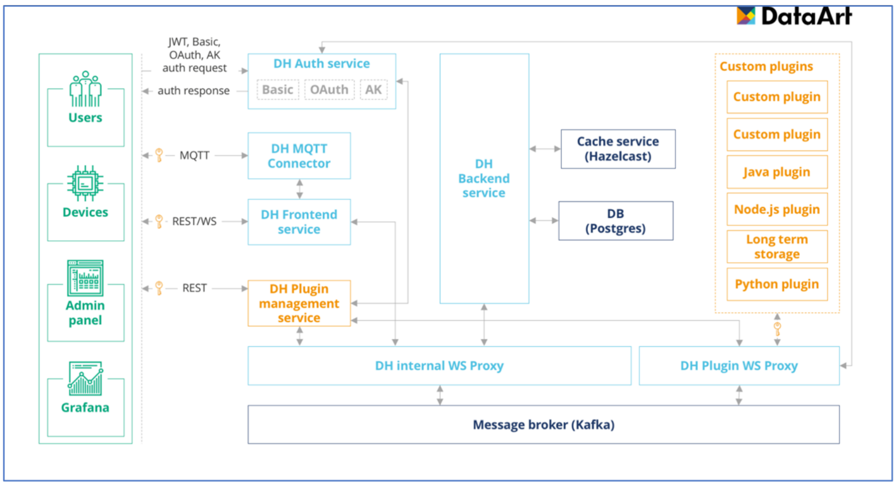

Figure 6. DeviceHive microservices architecture [64].

4.5. Mainflux

Figures 7 and 8 illustrate the details of the Mainflux IoT architecture [65], which is open-source for both private and commercial use. It is highly variable in deployment, scalable on an industrial level, and has persistent database storage with a hybrid (relational, NoSQL, and time-series) structure.

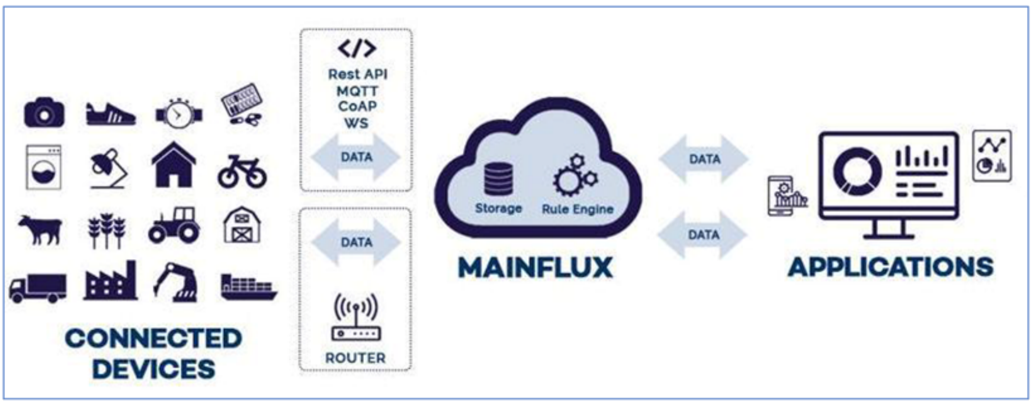

Figure 7. Mainflux architecture overview [65].

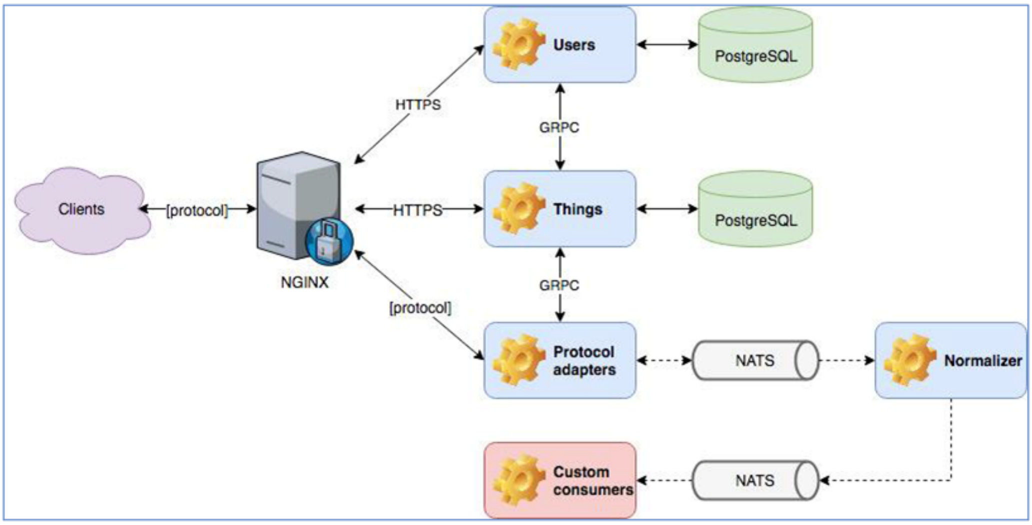

Figure 8. Mainflux architecture [65].

4.6. SiteWhere

The SiteWhere platform is designed to ingest, store, process, and assimilate device inputs [66]. SiteWhere can be deployed on cloud platforms such as AWS, Azure, and GCP and on premises, as well as supporting the provisioning of Kubernetes clusters (Figure 9).

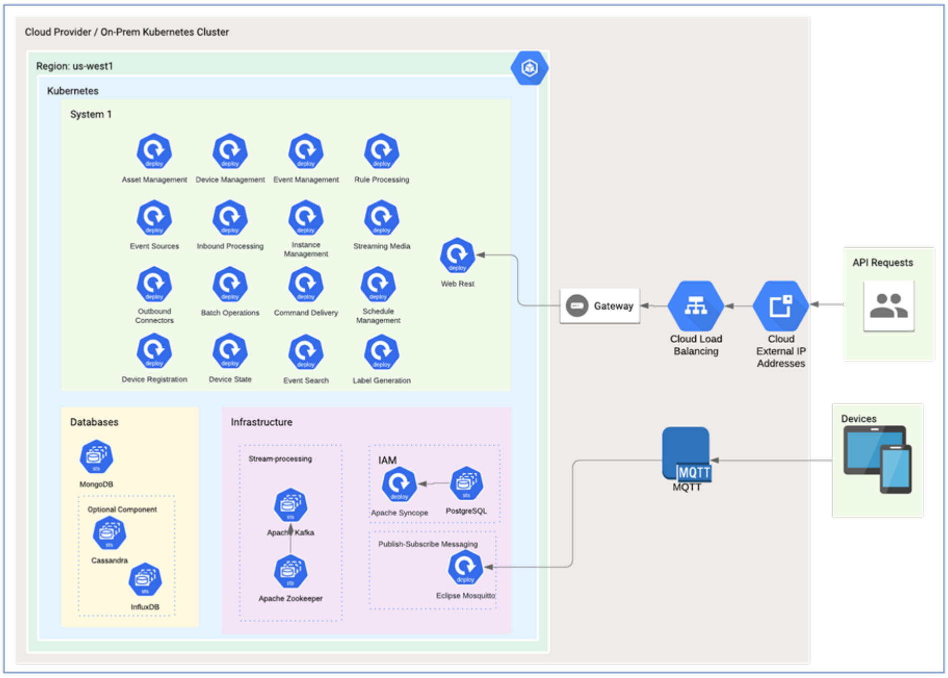

Figure 9. SiteWhere architecture [66].

4.7. EdgeX Foundry Platform

Figures 10 and 11 depict the design of the Edge Foundry framework. This platform facilitates the collaboration of developers, technology vendors, and end users by sharing expertise and resources, as well as benefiting from economies of scale. This collaboration leads to the quicker achievement of business goals with reduced expenses and lower risks. EdgeX stands out due to its extensive scope, wide-ranging industry backing, established credibility, substantial investment, and commitment to an open-source license of the vendor-neutral Apache 2.0, overseen by the Linux Foundation's LF Edge group. Consequently, EdgeX plays a pivotal role in driving digital transformation and the integration of AI in various IoT applications and sectors, as noted in [5].

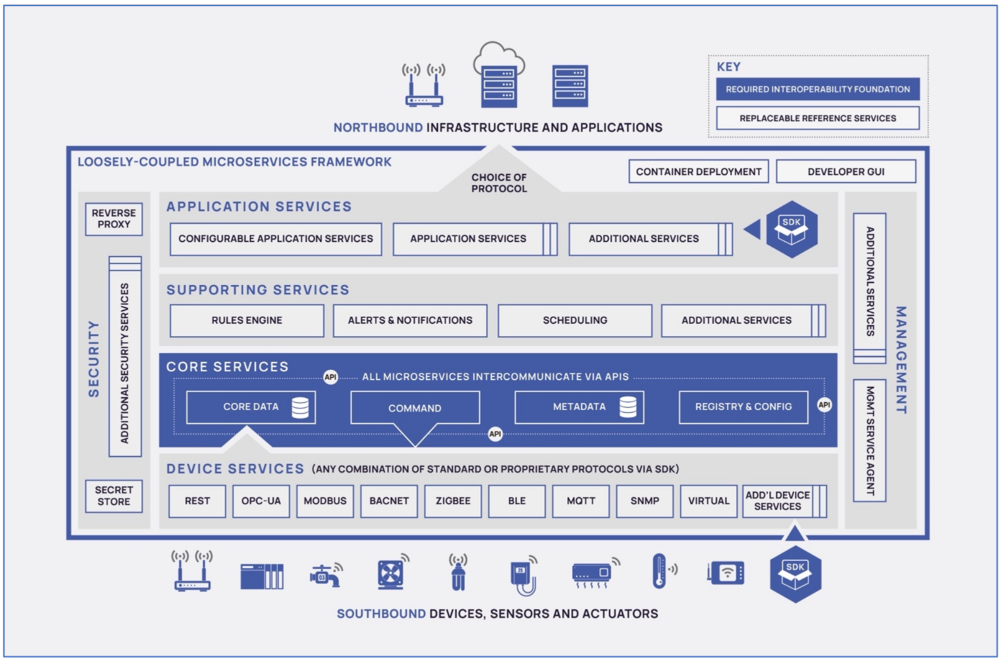

Figure 10. EdgeX platform architecture [5].

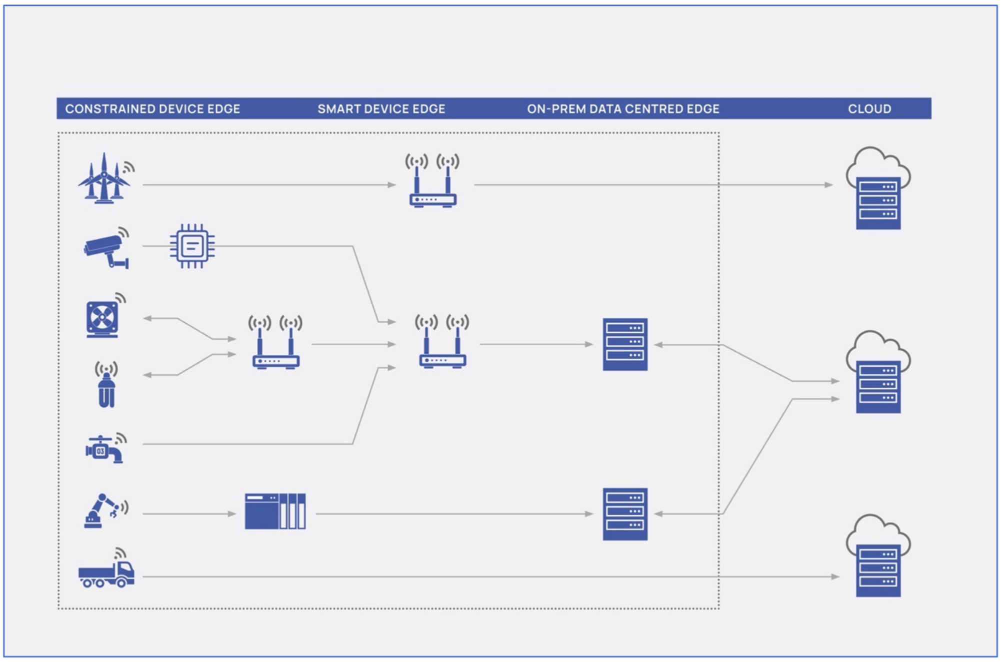

Figure 11. Edgex foundry project scope [5].

EdgeX Foundry is dedicated to harnessing the potential of Edge Computing by adopting cloud-native concepts such as modular microservices and platform independence. The objective is to develop a structure that is tailored to the unique demands of edge environments of the IoT [5]. This includes handling various connectivity protocols, ensuring security, managing systems across widespread computing nodes, and adapting to devices with limited resources. The project excels in scenarios that require immediate local decision-making and where automation and actions are driven by diverse data sources. EdgeX is actively working to solve crucial interoperability challenges at edge nodes and standardize data across different directions—south, north, east, and west—within a decentralized IoT edge framework [5].

4.8. Thin-ede.io

Thin-edge.io represents an open-source solution designed to develop connected devices that are efficient and secure, as shown in Figure 12. This platform operates independently of the cloud while offering essential support for cloud integration and device administration. It includes an array of preconfigured modules, easy-to-integrate connectors for various cloud platforms, device certificate management, comprehensive monitoring, and integrated software and firmware management [67].

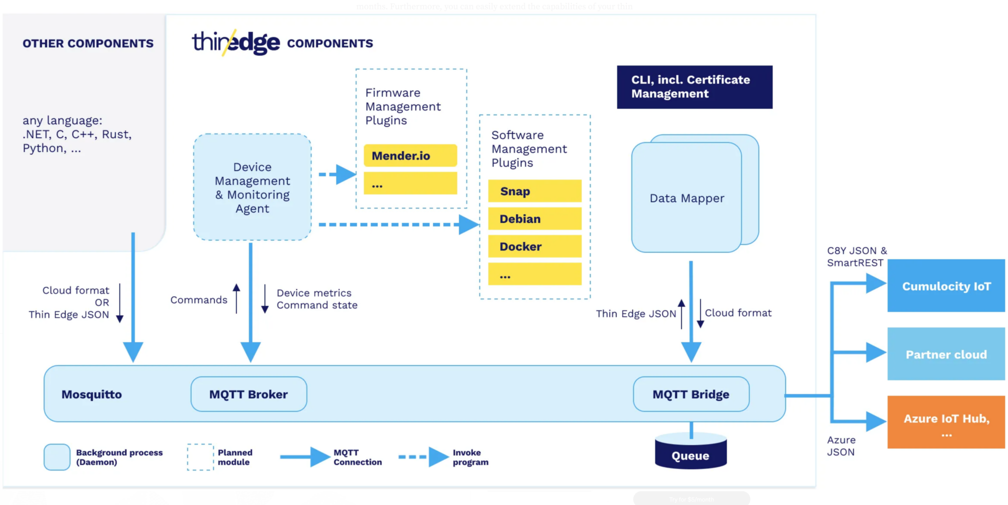

Figure 12. Thin-edge.io architecture [67].

Diverse components provided by various players in the IoT space can be utilized to construct telemetry applications. These components offer a spectrum of functionalities, ranging from basic connectivity with the IoT protocol to advanced features such as stream analytics, machine learning-powered systems, or specialized application processors [67]. The architecture of thin-edge.io is designed for flexibility and can be expanded using different programming languages. At the core of thin-edge.io's architecture are processes that interact through an MQTT bus [67]. This bus links to the cloud, channeling messages to cloud-designated topics. Furthermore, a standard data format is employed, enabling component interaction for a telemetry data exchange without dependence on cloud-specific formats. Mapper processes play a key role in converting this standard data format into cloud-specific messages and the other way around.

4.9. Thinger.io

Figure 13 illustrates Thinger.io, a comprehensive IoT cloud platform with various key features [67]. It enables easy connectivity for devices, either through the admin console or the REST API. In addition, it integrates with IFTTT, providing real-time data in an attractive dashboard. The main objective of the platform is to make IoT accessible worldwide by simplifying the prototyping, scaling, and management of connected products. It offers a free IoT platform for initial learning and prototyping with a smooth transition to a Premium Server for larger-scale deployments. The system is incredibly simple, requiring only a few lines of code to connect devices and access data via the web-based Console, which can handle numerous devices with ease. Additionally, it is hardware-agnostic, integrating devices from various manufacturers.

The Thinger.io platform is designed for optimal scalability and efficiency, allowing the management of numerous IoT devices while keeping computational demands, latency, and bandwidth usage to a minimum. The dedication of this platform to open-source values is demonstrated through the public availability of its key components, libraries, and application source code on GitHub, licensed under the MIT license [68]. It is compatible with a diverse array of devices, including those running on Linux, Arduino, Raspberry Pi, and

MQTT, as well as edge technologies such as Sigfox and LoRaWAN. Thinger.io's data buckets enhance scalability and efficiency, providing a solution for the real-time aggregation and storage of IoT data. The platform also offers a variety of widgets for creating visual displays and dashboards for both real-time and historical data. An integrated Node-RED rule engine facilitates the trigger of events and the manipulation of data [68]. Furthermore, the platform supports plugins for third-party service integration and offers a fully customizable front end, allowing users to tailor the platform's visual elements, such as color schemes, logos, and domain customization, to align with their branding.

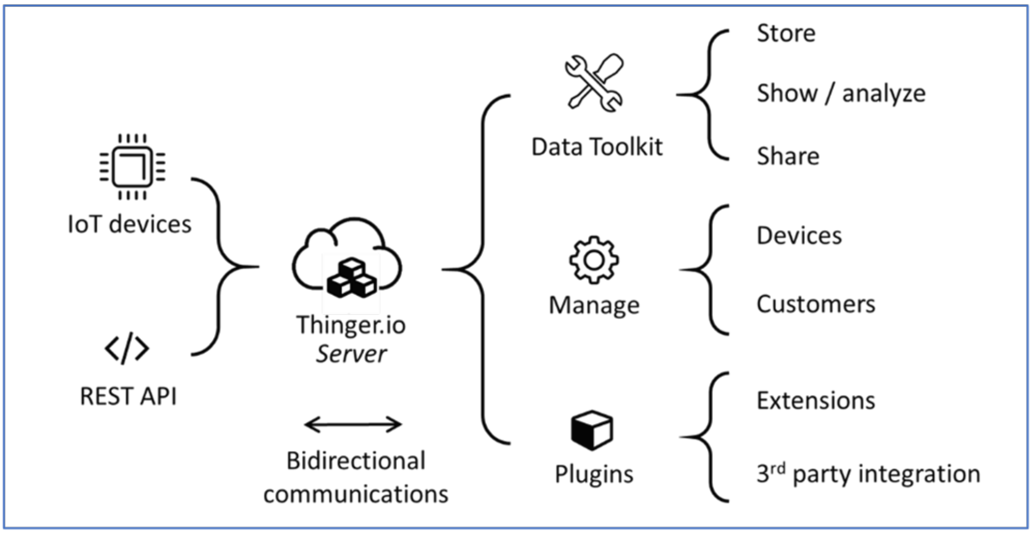

Figure 13. Thinger.io framework [68].

4.10. Comparison of Open Edge/IoT Platforms

Table 4 offers a systematic comparison of various platforms that meet the needs of IoT and edge computing. Each platform was evaluated according to several criteria:

- Open-source indicates whether the source code of the platform is accessible and modifiable.
- Resource requirements classify the degree of resources needed for a platform (such as CPU or memory), classified as low, medium, or high.
- Persistent database indicates whether the platform provides persistent data storage solutions.
- Visual reflects the platform's ability to provide visual interfaces or dashboards to represent data.
- Edge support refers to the platform's readiness to operate on the edge of the network, closer to data sources.
- Device management assesses whether the platform includes tools and features for managing IoT devices.
- Support IoT ensures that the platform supports Internet of Things protocols and standards.

Table 4. Comparison of IoT-Edge platforms.

Platform	Opensrc	Resource req	Persistent db	Visual	Edge	Device mngt	Supports IoT
Thingsboard [62]	Yes	Moderate	Yes	Yes	Yes	Yes	Yes
EdgeX [5]	Yes	High	Yes	Yes	No	Yes	Yes
OpenRemote [6]	Yes	High	Yes	Yes	Yes	Yes	Yes
DeviceHive [6]	Yes	High	Yes	Yes	No	Yes	Yes
Thin-edge.io [67]	Yes	Low	No	Yes	Yes	Yes	Yes
SiteWhere [66]	Yes	High	Yes	Yes	No	Yes	Yes
DeviceHive [64]	Yes	Moderate	Yes	Yes	No	Yes	Yes
Mainflux [65]	Yes	Low	Yes	Yes	No	Yes	Yes

The platforms listed include Thingsboard, EdgeX, OpenRemote, DeviceHive, Thinger.io, SiteWhere, another DeviceHive entry, and Mainflux. The functionality of each platform is marked as "Yes" for availability or "No" for absence, giving a clear overview of its capabilities, allowing a brief comparison, and helping stakeholders choose the appropriate platform for their specific IoT and edge computing requirements.

5. IoT in Different Sectors

The IoT is a network of interconnected smart devices that can collect and transmit data, as discussed in Section 2.1. This technology has been adopted by many governing bodies in various industries, and the following subsections explore some of the most prominent sectors where IoT is being used. Additionally, this section provides an overview of the general requirements of IoT solutions and the specific requirements of each sector.

5.1. Industry 4.0

Industry 4.0 is the fourth industrial revolution, which is marked by a shift to digitalization. As shown in Figure 14, it is one of four industrial revolutions.

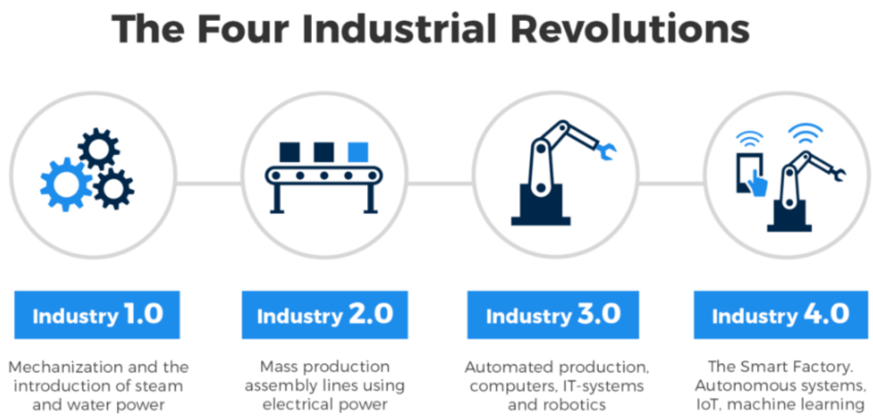

Figure 14. The four industrial revolutions ([69]).

The first industrial revolution saw the introduction of mechanization and steam power in manufacturing. It was followed by the second revolution, which brought about mass-production assembly lines and electricity, resulting in a dramatic increase in production efficiency. The third revolution brought about the utilization of automation, computers, and robotics to facilitate the management of production. The fourth revolution has brought autonomous systems, the IoT, and machine learning to monitor and control manufacturing processes.

Investing in Industry 4.0 has several advantages, the most obvious being improved productivity through automation. It also helps reduce waste and improve yield, two of the most important factors in development. Additionally, Industry 4.0 increases sustainability through real-time monitoring and reduces maintenance costs for future factories. Automation also increases the agility of production, giving manufacturing companies a competitive edge by allowing them to quickly adapt to the production of newly introduced products [69]. This sector is referred to as smart manufacturing in the remainder of this research paper.

5.2. Industry 5.0

Industry 5.0 is a progression from Industry 4.0, which was centered around the mechanization of production. This new period of time emphasizes on the reintroduction of human touch and craftsmanship into the manufacturing process. In comparison to Industry 4.0, which was distinguished by the incorporation of digital technologies, the IoT, and machine learning to enhance production, Industry 5.0 is distinguished by cooperation between people and intelligent systems.

The upcoming revolution is anticipated to combine the creative and cognitive capabilities of human workers, enhance personalization and sustainability, and increase the efficiency of smart automation. Industry 5.0 strives to achieve a balance between productivity and social aspects, such as the welfare of employees and environmental concerns. Its aim is also to enhance the customization of production and better meet consumer requirements.

The implementation of Industry 5.0 strategies is expected to bring about advancements in product design, customer satisfaction, and ecological sustainability, as well as guarantee a comprehensive approach to industrial growth, including ethical considerations in addition to technological advancement [70].

5.3. Agriculture

IoT devices are employed in a wide range of areas, including the agricultural sector. The IoT has a major role to play in agriculture, allowing for cost-effective processes with a decreased need for manual labor due to real-time monitoring and automated systems [71]. Smart agriculture technology enables farmers to have better control over the process of growing and cultivating crops and raising livestock [72]. Growers and farmers can use IoT to reduce waste for utilities such as water, fertilizer, and fuel for farm vehicles, as well as to increase the productivity of various crops and products harvested from farm animals. It is essential to be aware that the majority of IoT solutions in the agricultural sector face a range of difficulties when it comes to being accepted. The most significant issue is that IoT solutions are usually diverse, meaning that there is no single solution that fits all. This is because of the variety of participants in the food system, from very large to very small [43].

5.4. Healthcare

Governments prioritize healthcare due to the effects of rural urbanization, population growth, a decreasing birth rate, population aging, and economic growth. The IoT can be used to address these social issues in the healthcare sector. Smartphones can be utilized to monitor medical parameters and give advice to patients [73]. There are multiple enabling technologies of IoT in healthcare, such as communication technologies that bridge geographic boundaries, provide a rapid response to clinical emergencies, and enable medical consultation and communication with medical images and video data. Location technology can be used to track individuals with particular health and mental issues that require care. Sensors can be used to track patients' health, from heart rate to body temperature and glucose levels [74]. This technology can be used to monitor a variety of health indicators.

5.5. Smart Cities

Smart cities are a network of physical objects, vehicles, and buildings that are connected to the internet and can communicate with each other [50]. This technology is designed to make cities smarter, providing services to both the government and citizens. It can be used in a variety of areas, such as home automation, smart grids, energy management, traffic control, air pollution, water, weather, and surveillance systems [75].

5.6. Logistics

The IoT can be used in a logistics setting to track the technical state of a vehicle and the driving style in real time. This technology gathers information on the position, velocity, and orientation, as well as any traffic infractions, which can be viewed in the transportation management system. It allows for control over fuel consumption, the timely detection of vehicle malfunctions, a reduction in emissions to support environmentally friendly practices among transport companies, and real-time navigation in congested areas [45].

6. Example IIoT Use Cases

This section provides examples of projects that have been completed that involve the development of an IIoT system.

6.1. Industry 4.0

Fastenal, a Minnesota-based industrial supply company, has been providing businesses with the materials and supplies they need to manufacture products, protect personnel and equipment, and construct buildings since October 2016 [76]. It has implemented MachineryMetrics in its production facility and has since extended its use to other locations. The goal was to gain insight into downtime, quality issues, and machine utilization, as well as to introduce advanced technology for further enhancements [76]. This case study aimed to answer questions about the implementation of certain technologies. Interviews revealed that the challenge was to find something that was compatible with the company's strategy and processes [76]. The goal was to enhance the management and collection of real-time information. MachineMetrics was selected because of its user-friendliness and the availability of real-time data. Moreover, it was a unique system due to its flexibility and responsiveness [76].

A business in the mining sector is modernizing its operations with the help of Industry 4.0. To make the best decisions, it is necessary to have a continuous stream of data between the enterprise level and shop-floor systems [77]. Mining companies are attempting to reduce their expenses and overhead by producing more with fewer resources [77]. A mine is using SAP as its ERP system, but it is not connected to other systems, so there is no access to real-time information. The information gathered is usually exported to Excel spreadsheets and sent to the shop floor and other systems at the mine [77]. All the data are manually collected and imported into the ERP software, and the company is investigating integrating SAP ERP with other systems at the mine. This implementation would create a semi-autonomous mining system that seeks to enhance both productivity and efficacy in the mine. The proposed implementation utilizes both vertical integration with a centralized data repository to provide access to all participating systems and horizontal integration between collaborating companies for various functions, such as fuel supply, tire supply, fleet management, and machine supply [77].

6.2. Agriculture

Many agricultural businesses provide solutions for tracking the health of crops and their environmental effects. Milesight, for instance, implemented a project to provide a wireless solution to meet the needs of customers in Austria [78]. This project was centered on collecting, interpreting, and displaying data from multiple LoRaWAN sensors incorporated into a crop health management system. This is essential to safeguard plants from extreme weather conditions when they are particularly susceptible to diseases.

This project was a challenge due to various metrics, such as temperature, humidity, and sunlight, that are hard to collect data on and process manually. As weather conditions can be unpredictable, manual data collection can be difficult or even impossible [78]. The project was successful in reducing costs by decreasing the number of people needed to monitor crops. Furthermore, farmers were able to adjust soil- and crop-specific fertilization and plant nutrition based on visualized data, resulting in an increase in productivity [78]. In conclusion, the project was a success that enabled farmers to increase efficiency and productivity in their plots.

6.3. Healthcare

The Swedish startups Cuvina and Tele2 IoT have collaborated to enable healthcare providers to remotely monitor patients [79]. The solution combines a cellular-connected laptop or tablet with IoT sensors that measure vital data such as heart rate, temperature, weight, blood pressure, and insulin levels. Security is of utmost importance, as medical data are highly sensitive, and many privacy issues are at stake. Cuvina is also planning to integrate third-party products such as connected pill dispensers into its solution, which is intended to act as a centralized hub for various healthcare devices and services [79]. This will enable an interoperable system, allowing devices collecting data to communicate with each other in order to provide better monitoring services to health providers.

The European Union is looking into e-health matters and potential solutions through a variety of initiatives. The TopCare project, based in Europe, is creating platforms for home care to bring medical care to patients in their own homes and track hospitalization [80]. The TeleCare project concentrates on systems for remote monitoring to help elderly people stay independent [81].

6.4. Smart Cities

Sensorise has incorporated cutting-edge technology to read a variety of sensors, gateways, IoT platforms, and web and mobile applications to enable the deployment of connected services at a low cost and in a timely manner [82]. This project provides utilities and municipal authorities with real-time visualizations of resources used in public buildings, such as energy and water consumption, distributed renewable products, and indoor air quality. The platform offers services like forecasting, decision support, and remote control features that allow for dynamic resource planning [82]. Additionally, the platform includes security measures to protect against potential threats. It also utilizes a standardized API for third-party tools' integration, enabling open standards and interoperability. Furthermore, it supports smart energy management functionalities to predict short-term energy demands, tools to interact with the energy market, and analytics to facilitate a virtual energy exchange [82].

Cities around the globe are utilizing the IoT for smart cities. For instance, Dublin has a smart rain sensor project that monitors rainfall levels to prevent flooding [83]. San Diego has a smart street light project that uses sensors to collect data on parking spaces, vehicle counts, pedestrian and bicycle counts, temperature, and humidity [83]. Amsterdam has a blue force tracking project to demonstrate and enhance digital security by detecting unusual behavior [83].

7. Current IoT Trends Analysis

To understand the current state of the IoT, a process called Extraction Transformation and Load (ETL) [84] is used. This process involves three steps that create clean, accessible, and simple data that can be used in this study.

7.1. Methodology

This section provides an overview of the main tasks involved in the process. These tasks included analyzing the requirements of different sectors for IoT solutions, providing relevant examples, analyzing case studies, extracting and processing data, visualizing the data, and discussing market trends and the utilization of the visualized data. A quantitative analysis of the requirements for some sectors of IoT solutions was conducted to identify general and specific requirements for different sectors. The goal was to establish standard requirements that can serve as a guide for potential IoT solution requirements when creating IoT solutions.

In order to determine the areas of the market with the most potential, the advantages and difficulties, as well as the role of embracing IoT solutions in different sectors, were studied and demonstrated with example cases. Platform Patsnap was used to gather data on the popularity and IoT projects [85]. A variety of metrics were used to recognize the current IoT trends, such as the market capitalization of a company, its location, its revenue, and its patent value. The data were processed using Python, and visualizations were created with PowerBI.

This study provides a method to recognize which areas and industries have great potential for the development of IoT solutions. A discussion is included to determine the key features of the data and what to focus on to identify these areas, with some examples and visuals provided. The model in Figure 15 outlines the key stages of data-processing and analysis. The first step is to gather data using search criteria such as sectors and IPC codes to eliminate unnecessary information. The second step is to transform the data, create new tables, and group patents based on application year and IPC codes to calculate the value growth rates. The third step is to visualize the data, making useful charts to allow for trend analysis. The fourth step is to explain what to look for in the visuals and how to recognize certain trends with some examples of trending IPC groups.

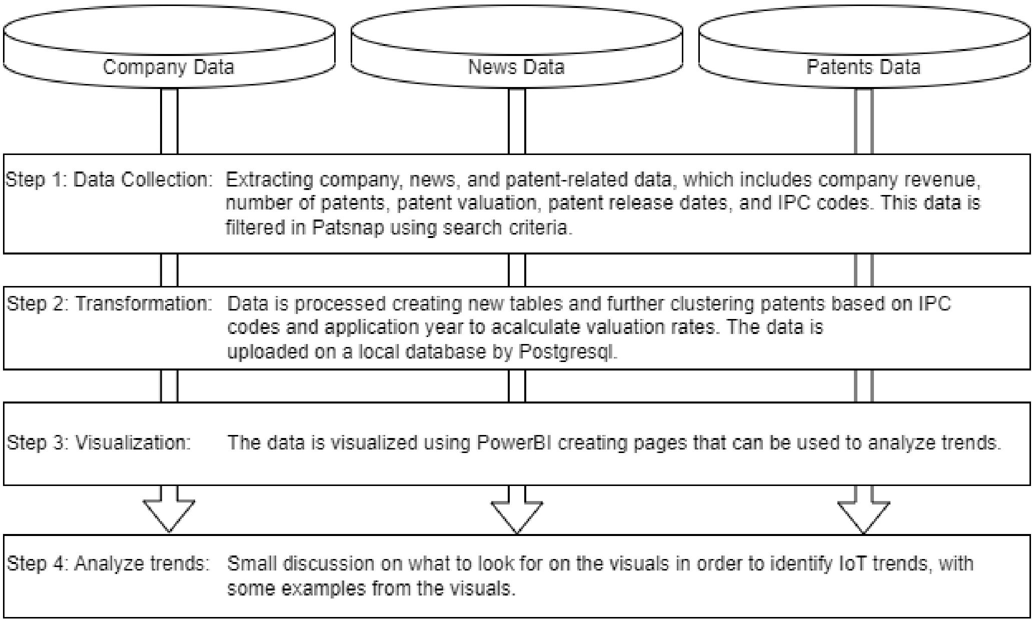

Figure 15. Four steps for processing and analyzing data.

7.2. Data Extraction

To identify the current trends in the IoT, data were collected from Patsnap, a platform used for research purposes. The data included information about companies in various industries, as well as news related to the patents they have created or other activities on the market. To gain insight into the state-of-the-art applications of the IoT in various sectors, patent information was collected. The sectors examined are agriculture, healthcare, logistics, manufacturing, and smart cities. However, since some IoT applications do not include "IoT" in their description, a basic semantic search would not be enough to identify all relevant patents. Therefore, the IPC scheme [7] was used to further filter the data. The hierarchy begins with sections labeled with alphabetically increasing characters from A to H.

Information and Communication Technology (ICT) is classified as part of the G category of physics. However, IoT applications are not limited to this section. According to the WIPO, IoT is classified into class G16, which is specifically for ICT applications that are "specially adapted for specific application fields" [86]. This class does not include pattern recognition, digital computing, data-processing systems, image data-processing, or image generation, which are covered in group G06K 9/00, subclass G06Q, and subclass G06T, respectively. When taking into account the definition of the IoT and the application areas, it can be speculated that these areas are also useful for classifying IoT solutions.

In addition to the hardware and network requirements set for IoTs, H04 (an electric communication technique) covers the areas applicable for any network devices used and discussed in Section 2.3. Table 5 outlines the classes and sub-classes that encompass the IoT from various perspectives, including software, hardware, and calculation aspects. However, classes G06 and H04 include other areas for patent classification that are not related to the IoT, such as telephonic communication for H04L. It is beneficial to include these areas as some applications do consider IoT patents that use them. Class G16 is thought to be the most pertinent to IoT solutions, but patents are not always classified in this class. Other subclasses of G16 are also useful, and the entire class was taken into account in this research, with particular emphasis on G16Y. Patsnap's data include both all the IPC groups a patent is classified in and the main IPC group for the patents. During the filtering process, the IPC groups were used, but the data include the main IPC group for visualization purposes. This is why some other groups appear in the data, but the idea is that the patents are related to the IPC subclasses mentioned in Table 5.

Table 5. Overview of international patent classification (IPC) classes and subclasses.

IPC Class	Description of Class	IPC Subclass	Subclass Description
G06	Operations related to computing, Calculation, and counting	G06K	Methods and systems for data recognition and representation; dealing with record carriers
		G06Q	Data-processing systems or methods tailored to specific business, financial, management, or forecasting applications
		G06T	Processes for image data-processing or generation
G16	ICT specialized for specific application domains	G16Y	ICT advancements particularly designed for IoT applications
H04	Techniques in electrical communications	H04B	General transmission techniques
		H04H	Techniques related to broadcast communication
		H04L	Digital information transmission

7.3. Data Transformation

Python was employed to convert the data with libraries such as pandas, numpy, psycopg2, datetime, string, and os. The purpose of this transformation was to make the data more accessible for PowerBI to visualize. Tables were created to store the data for each sector, forming a star schema and uploading it to a local PostgreSQL database. Initially, a table of sectors was created, containing the names of each sector. The hierarchy of folders in the directory and the Python code are scalable and reusable, allowing research personnel to add more sectors and data as needed.

Two tables were created to store information about companies and their sectors: a company table and a companies table. The industry table stores the companies' index as a foreign key across industries, which are data included in the company Excel file used in Patsnap's algorithm to classify companies. The news table is related to both the sectors and the companies, allowing us to link them and create visuals. The patents table is connected to the sectors and subclasses table, which includes the main IPC Groups. Patsnap's data include a column with all the IPC groups and a column with the dominant IPC group of each patent. Four more tables were created to store the IPC instance's valuation rates for each year, which are linked with the IPC tables, and each IPC with its respective years is assigned a rate calculated using Formula (1) [87]. Two tables were created to store information about companies and their sectors.

The industry table stores the companies' index as a foreign key across industries, which comprises data included in the company excel file used with Patsnap's algorithm to classify companies. The news table is related to both the sectors and the companies, allowing for the connection of the two and the creation of visuals. The patents table is connected to the sectors and subclass table, which includes the main IPC Groups. Patsnap's data include a column with all the IPC groups and a column with the dominant IPC group of each patent. Additionally, four more tables were created to store the IPC instance's valuation rates for each year, which are linked with the IPC tables, and each IPC with its respective years is assigned a rate calculated using Formula (1) [87].

$$ValuationGrowth = \frac{VCY - VPY}{VPY} \tag{1}$$

7.4. Visualisations

PowerBI is a business intelligence tool that allows users to import data from a PostgreSQL database and create insightful dashboards. This enables them to identify current trends and potential areas of growth. An example of this is the overview of the company data for all sectors, as seen in Figure 16. This provides an understanding of the main players in the IoT market.

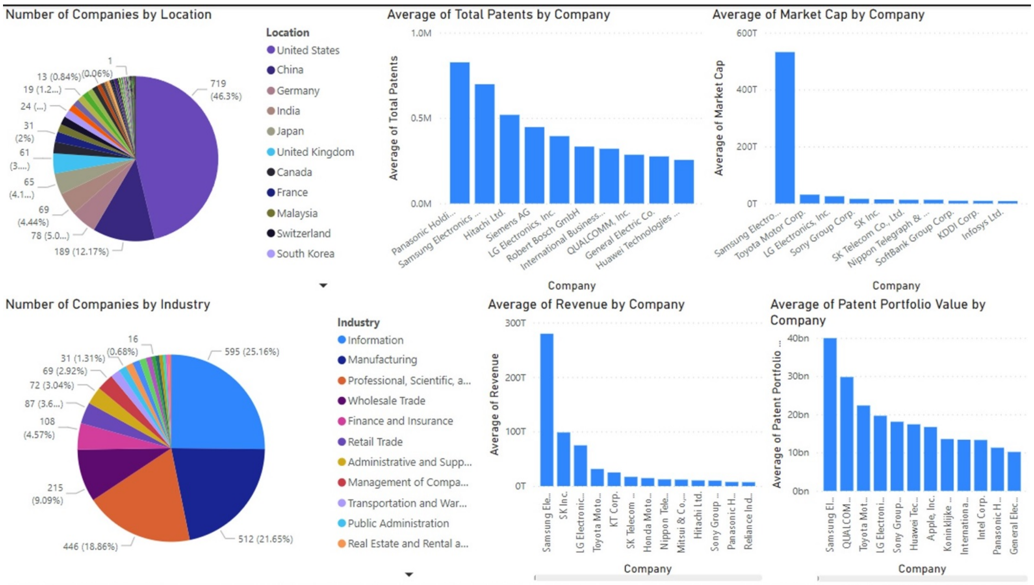

Figure 16. Company overview.

Most of the businesses in the data set are located in the United States, with Panasonic Holding Corp., Samsung Electronics Co., Ltd., and Hitachi Ltd. having the most patents. The information, manufacturing, professional, and scientific industries are the most common. The graph also displays the average revenue and value of the patent portfolio for each company. To gain a greater understanding of the current trends in IoT, we can look at the number of news stories about each company (Figure 17).

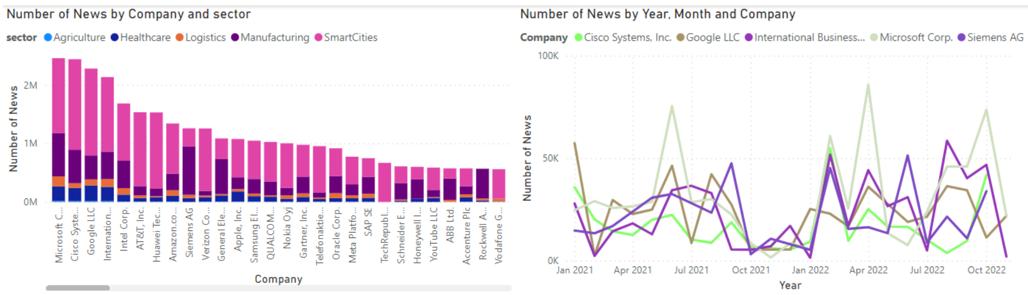

Figure 17. News per company and sector.

A visual representation of the patent data is presented in Figure 18. The first pie chart illustrates the number of patent applications per IPC section, with physics being the most commonly used classification index. The second line graph displays the number of applications by IPC class for the different sectors, with computing, calculating, or counting being the most popular class, particularly in the manufacturing sector, where more than forty-five thousand applications have been made. The next graph shows the number of applications by IPC subclass, with electric digital processing being the most popular. The following graph displays the number of applications by IPC group, with administration and management being the most popular. A timeline graph then shows the number of applications by IPC group, and finally, a graph shows the number of cites of patents by IPC group.

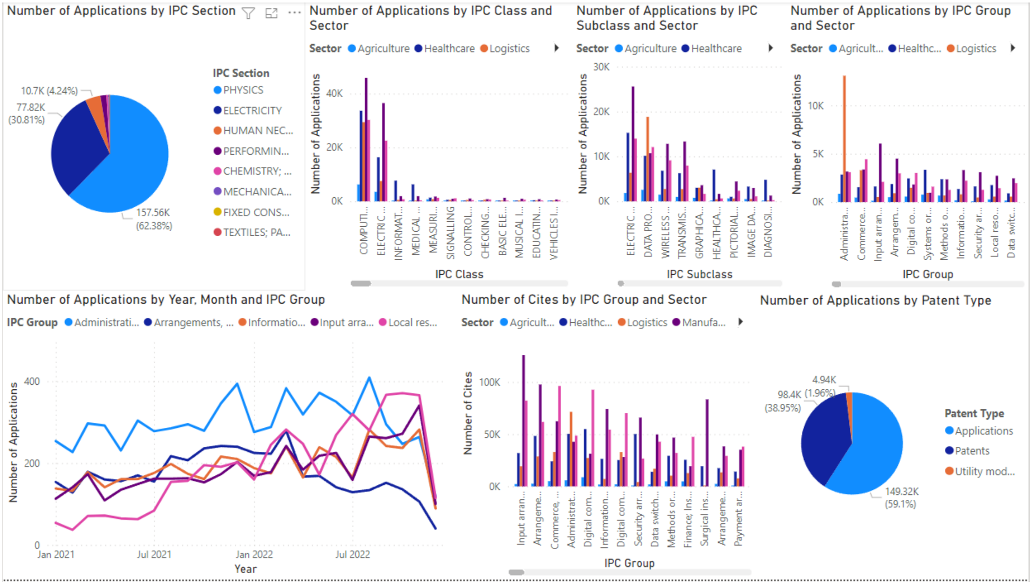

Figure 18. Patents overview.

Examining the valuation of patents is a key factor in understanding current trends in the IoT. Figure 19 shows a visual representation of this analysis, with two pie charts illustrating the valuation of different sectors and IPC sections. The timeline shows the valuation of the sectors over the past two years, while three separate charts display the valuation of patents in IPC class, IPC subclass, and IPC group. The data reveal that manufacturing and smart cities have a slight advantage when it comes to the valuation of IPC groups.

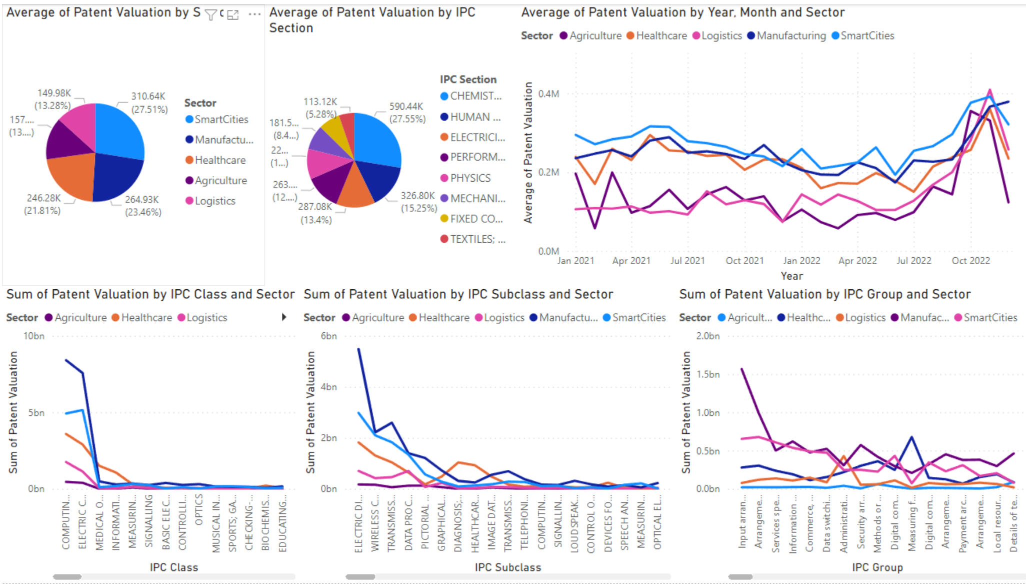

Figure 19. Patent valuation.

It is worth exploring the rate of growth in valuation, as shown in Figure 20. This figure includes line graphs that illustrate the rate of IPC classification over the last five years for the top 20 IPC groups, as well as a line chart that displays the number of patents over the same period. Additionally, a line and column graph with the valuation in bars and the rate in a line for the past five years is included, as well as a table that shows the patents for which these IPC instances occur.

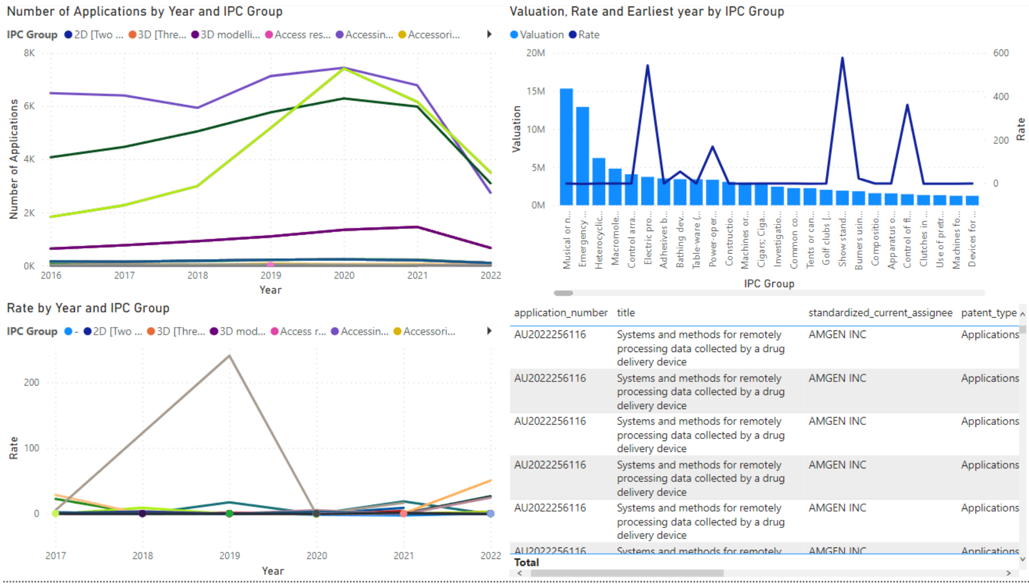

Figure 20. Rate analysis.

7.5. Result Discussion

The analysis of the literature in Section 3 enabled us to identify general IoT requirements and, more precisely, industry-specific requirements while also responding to the research question outlined in Section 1. Interoperability, real-time capability, user-friendliness, and security–privacy were the most common requirements among industries, making them essential for the successful launch of an IoT solution. The task technology fit model can be used to measure the effect of an IoT solution on an organization and assess its compatibility with business strategy and IT. These theories are critical to the success of an IoT solution.

The data collected can be used to identify areas where research can expand its contribution to the IoT. The generated figures can serve as a guide to help determine potential areas of focus. Company overview pages can be used to identify the leading organizations in the field. Figure 16 suggests that companies such as Samsung, Panasonic, and Hitachi are some of the major players in the market, with high revenues and a large number of patents. In areas where these companies are dominant, it can be difficult or even impossible to introduce a successful IoT solution. However, there are certain cases where a problem requires a high degree of customization, and smaller companies can focus on these scenarios. The number of news stories can also be used to gauge the market trend, as companies with a lot of news tend to attract people and organizations. Furthermore, certain patent data can be used to further investigate the areas in which these companies are more active.

It is worth considering the number of patents for each IPC section, class, subclass, and group. This can help identify which of these sections could be more promising (Figure 18). However, there are other factors to take into account, such as the viability of patents in certain areas. The lack of patents in a section or the following objects in the classification scheme may be due to risks, costs, or a lack of demand that makes that area unprofitable for organizations. Therefore, organizations should examine and address the factors discussed in Section 3.

Considering the worth of patents, we can determine where the IoT market is heading (Figure 18). The more investments in and the higher the valuation of patents, the greater the demand, but this could also mean that there are major players in the field and a highly competitive market. There are many IPC subclasses and groups with low patent valuations, which could potentially indicate low competition, but this is not always the best situation since those areas may not be popular at the moment. This could mean that, if researchers decide to invest in some of these areas, a key indicator would be to analyze areas with little competition and high demand. An example of this is that there are only a few patents with a high overall valuation, and the introduction of a new patent would result in the patent flourishing and also breaking the "monopoly" effect. An example of a highly competitive landscape in agriculture is in the group of "methods or arrangements for recognizing patterns," consisting of 455 patents and a total valuation of 61 million. To get an indication of this effect, we can calculate the average of the patent valuation with the number of patents.

The data depicted in Figure 20 enable us to understand which IPC categories have demonstrated the most significant expansion up to the year 2022. One particular group, "Advertising or display means not otherwise provided for," exhibited growth of 50.28% from 2021 to 2022. This group recorded two patents in 2022, collectively valued at over 8 million USD. When analyzing the number of applications from 2017 to 2022, certain groups emerge as notably active. These include "Affiliation to network, e.g., registration; Terminating affiliation with the network, e.g., de-registration, Administration; Management," and "Accessing, addressing, or allocating within memory systems or architectures." A combined bar and line chart in the figure provides insights into the overall growth rate and valuation over five years, yielding varied outcomes (Figure 20). The category "Musical or noise-producing devices for additional toy effects other than acoustical" ranks the highest in valuation despite a modest growth rate. The sector "Electric propulsion with power supplied within the vehicle" shows promising potential, boasting a nearly five million USD valuation and a remarkable 542% growth rate. "Control of fluid pressure" is another notable category, with a valuation of one and a half million USD and an impressive growth rate of 361%.

8. Discussion and Future Work

This research provides a way for researchers to gain insight from the visualizations created, which can reveal areas with high potential. The visualizations cover a broad overview of the competition in IoT solutions and the leading companies, as well as a more detailed analysis of the popular patents using the IPC classification scheme. It is important to note that these visualizations should not be used as a sole decision-making tool, and other factors should be taken into account. PatSnap is a great platform that offers a wealth of patent information and technology insights; however, much of the data is licensed and not publicly available. The data transformation methods discussed in Section 7.3 were used to address some of the incomplete data, but there is still room for improvement. Additionally, due to time constraints, future work should consider the IPC classification scheme. There are many patents in the visualizations that are described with different IPC codes outside the IPC sections and classes in Table 5. Although the data are mostly relevant, with some minor outliers, further processing of the IPCs of each patent would be necessary to create better visualizations of the mentioned IPC classes and subclasses.

9. Open IIoT Research Issues

The exploration of the IIoT and the use of open-source platforms and edge computing offer a wide range of possibilities. However, there are still some open research issues that need to be tackled to make the most of these technologies. According to our investigation, the following research issues should be addressed:

- Interoperability of open-source IIoT platforms: Platforms such as DeviceHive, and Thingsboard provide flexibility, but the interoperability between different open-source IIoT platforms and existing legacy systems is still a challenge. Research into the development of universal standards or middleware solutions that allow for a smooth integration could significantly improve efficiency and scalability across various industries.
- Security and privacy: The integration of IIoT into critical infrastructure has raised security and privacy concerns that should be addressed. To ensure the safety of these systems, research is necessary to create secure protocols that can protect against advanced cyber threats without sacrificing the efficiency and effectiveness of IIoT systems.
- Edge computing optimization: EdgeX Foundry and other similar platforms are enabling the processing of data to be closer to its source. This raises the issue of opti-

mizing the allocation of resources and the computational efficiency of the edge. This includes dynamic resource management, fault tolerance, and self-healing capabilities in edge computing nodes.

- Real-time data analysis: The IoT generates large quantities of data, and it requires real-time analysis to make timely decisions. To do this, advanced analytical algorithms and machine learning models must work within the limits of the edge computing system.
- Scalability and management of IIoT devices: The exponential growth of interconnected devices has created a need for research into scalable architectures and management tools that can handle the increased load while still providing performance and reliability. Such research is essential to ensure that these devices can be managed effectively.
- Energy efficiency: The energy requirements of IIoT devices, particularly when they are used in large numbers, present a major issue. To improve energy efficiency, it is necessary to investigate novel solutions such as green computing and energy-harvesting.
- Quality of Service (QoS): Achieving a high level of Quality of Service (QoS) in IIoT systems, particularly in mission-critical applications, is an area of ongoing research. This requires addressing network dependability, latency problems, and service continuity in the face of device mobility and changing environmental conditions.
- Customization and user-friendly solutions: The IoT has the potential to change many industries, but its implementation often requires a high level of customization to meet the specific needs of each sector. To make this process easier, research is needed to create user-friendly design interfaces and customization toolkits that can be used by non-experts to tailor IoT solutions to their individual requirements.
- Economic models for open-source IIoT deployment: The economic effects of utilizing open-source IIoT platforms are not completely comprehended. Investigating sustainable economic systems that can validate the expenditure in open-source technologies will be essential for broad acceptance.
- Legal and regulatory compliance: The adoption of the IoT into various industries has made it difficult to comply with legal and regulatory requirements. It is, therefore, necessary to investigate regulatory frameworks that can keep up with the growth in IoT applications.
- Patent analytics and valuation: The importance of intellectual property in the IIoT is undeniable, thus necessitating the creation of advanced techniques for patent analysis and evaluation. Such tools should be able to measure the influence of patents on market movements and pinpoint potential areas for innovation.

To make progress in the field of the IIoT, it is essential to bring together experts from various disciplines, such as engineering, computer science, economics, and law. It is also important to collaborate between academia, industry, and regulatory bodies to maximize the potential of the IIoT in the future.

10. Conclusions

This manuscript has explored the IIoT and its implications for the technological landscape. It is clear that open-source platforms and edge computing are driving the evolution of the IIoT, providing a range of new opportunities for industry sectors. DeviceHive, Thingsboard, and EdgeX Foundry are just a few of the platforms that are revolutionizing the traditional industrial paradigm by decentralizing data-processing and reducing latency and bandwidth constraints. This has enabled real-time analytics and decision-making. This study has meticulously explored the IIoT, from communication protocols and business intelligence integration to the alignment of business strategies with IT capabilities. The exploration of IoT applications in agriculture, healthcare, smart cities, and logistics provides a blueprint for the future, when the pervasiveness of the IoT will undoubtedly become a cornerstone of industry innovation.

This research has provided a comprehensive view of the IIoT space, combining qualitative and quantitative analysis to identify market trends, patent valuations, and growth rates. The IPC scheme was used to structure the study's sector analysis, allowing stakeholders to identify areas with high potential for IIoT deployment. The findings of this research emphasize the need for strategic alignment, market analysis, and intellectual property considerations to maximize the benefits of IIoT solutions. As we move into a new era of industrial sophistication, driven by the IIoT and open-source and edge computing technologies, it is essential for industries to embrace these changes and foster innovation that is not only efficient and sustainable but also able to adapt to the changing needs of the digital age.

The way ahead for the IIoT is evident: further investigation and advancement in open-source platforms, a close watch on market trends, and a thorough evaluation of sector-specific needs. This will help maximize the potential of the IIoT, allowing for a future where industries function with unparalleled intelligence, agility, and connectivity.

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Abbreviations

The following abbreviations are used in this manuscript:

IIoT	Industrial Internet of Things
IoT	Internet of Things
RFID	Radio-Frequency Identification
GPS	Global Positioning System
BI	Business intelligence
DDS	Data-Driven Support System
IT	Information Technology
BSP	Business Systems Planning
IPC	International Patent Classification
WIPO	World Intellectual Property Organization
ICT	Information and Communication Technology
QoS	Quality of Service
QoE	Quality of Experience
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks
BLE	Bluetooth Low Energy
NFC	Near Field Communication
LPWAN	Low-Power Wide-Area Network
AHP	Analytic Hierarchy Process
ETL	Extraction, Transformation, and Load

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