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Empowering the Food Industry through IIoT Platforms: Takeaways for IT/OT Integration in Industry 4.0

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Abstract: This paper explores the implementation of Industrial Internet of Things (IIoT) platforms to address challenges in adoption due to information technology (IT)/ operational technology (OT) integration difficulties. The study uses a case from food manufacturing and supply. We outline specific requirements for IIoT implementation, leveraging empirical data from Danish food manufacturers and industry reports. By applying the Quality Function Deployment (QFD) method, we assess how 10 Microsoft Azure IoT functionalities (as an illustrative example) align with industry requirements, thereby discussing design considerations. In addition, we demonstrate practical implications in Aalborg University's Industry 4.0 learning factory to present a high-level architecture for IIoT-connected factory systems through Unified Modeling Language (UML). Our study highlights the significance of IT/OT integration for IIoT success and offers a blueprint for efficient data exchange and process control. The findings emphasize the importance of aligning technology choices with industry-specific requirements and provide future research directions for IIoT in brownfield manufacturing. Our results indicate *Scalability* and *Device Connectivity* as core functionalities for successful IIoT adoption, with each accounting for high percentages of importance of 19% and 16%, respectively. The paper contributes to Industry 4.0's data integration and enhances food industry operations. Future work will explore additional complexities to enhance IIoT implementation.

1. Introduction

1.1. Problems with industrial supply in food systems

The term 'food system' covers a network that involves all elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities related to the production, processing, distribution, preparation, and consumption of food, along with the resulting socioeconomic and environmental outcomes [1]. Industrial supply is a key component of the food system, ensuring food provisioning and healthy food access. For example, common supermarket dairy products such as milk and cheese undergo a series of industrial processes, including pasteurization, homogenization, and fermentation, to be prepared for distribution and consumption. Nonetheless, the industrial food supply faces several challenges that require innovative technological solutions. Some of these challenges are:

- **Food safety**: Problems such as adulteration, mislabelling, and contamination undermine the transparency and reliability of supply chains. Cases like horse meat fraudulently labelled and sold as beef in Europe [2] raised concerns about the supply chain's lack of transparency. Blockchain technology has gained popularity as a solution to enhance transparency in these contexts [3].
- **Affordability and healthy food access**: Many countries are experiencing food inflation, and in the UK, the price of food and non-alcoholic beverages rose by 17.4% in 2023 [4]. This situation limits low-income communities from purchasing healthy fresh food, exacerbating health inequalities.
- **Food shortages and food waste**: Food shortages disrupt societies and trade, often evident in empty shelves of supermarkets (scarcity of certain food products) and food waste. These instances highlight the lack of supply chain coordination that should sync manufacturing and distribution.

To address these challenges of product traceability and supply chain visibility, the principles of Industry 4.0, particularly information transparency and interconnection, emerge as potential solutions. The Industrial Internet of Things (IIoT) is a central concept in Industry 4.0's smart factories [5], which envisions a network of connected devices and services enabling seamless data exchange and coordination [6].

1.2. Related work on IIoT and its relevance in the food industry

The IIoT concept is central to the Industry 4.0 framework. Boyes, 2020 [7] define IIoT as:

> *A system comprising networked smart objects, cyber physical assets, associated generic information technologies and optional cloud or edge computing platforms, which enable real-time, intelligent, and autonomous access, collection, analysis, communications, and exchange of process, product and/or service information, within the industrial environment, so as to optimise overall production value. This value may include; improving product or service delivery, boosting productivity, reducing labour costs, reducing energy consumption, and reducing the build to-order cycle.*

IIoT integrates physical devices and data communication to establish a connected, intelligent industrial ecosystem that tackles pressing industry challenges. In supply chain contexts, IIoT manages disruptions through dynamic inventory management, quality control, and product tracking. For example, it provides actionable insights within factories,

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supported by predictive maintenance that significantly curbs machine downtime and optimizes resource utilization [8].

While literature highlights IIoT system design considerations, including device connectivity, data transmission, and security protocols [7], there are limited studies on the convergence of information technology (IT) and operational technology (OT) that pose architectural and security challenges. ISA 95, a popular industrial automation standard, advocates vertical integration of systems with a hierarchical structure, conflicting with Industry 4.0's distributed networked architecture vision (see Fig. 1). This challenges the integration of IIoT platforms into existing factory systems in brownfield manufacturing environments.

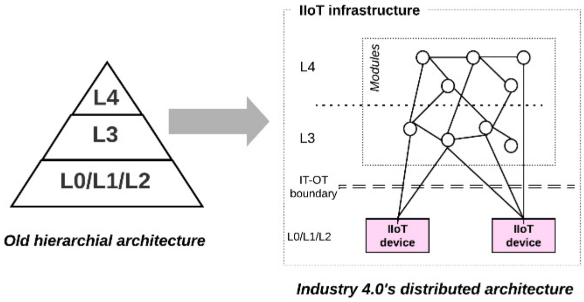


Fig. 1. *IIoT integration into existing ISA 95 structure in a brownfield manufacturing environment* [9] [10]

Furthermore, existing low computational capabilities of operational technologies can fail to support the necessary cryptographic protocols for IT/OT security, exposing the industrial control systems susceptible to attacks [11].

IIoT architectures depend on sensor integration, modern communication protocols (e.g. MQTT, OPC UA, CoAP), and cloud-based platforms for near real-time data processing demands [12]. IIoT applications are versatile in diverse sectors such as manufacturing, agriculture, healthcare, building management, smart cities, and logistics. Each sector presents its unique set of challenges and implementation strategies. In the food industry, IIoT faces challenges adapting to diverse and often digitally immature supply chains involving small-scale businesses and cottage industries.

Food supply chains' complex and interconnected nature demands real-time monitoring and data-driven decision-making. IIoT solutions have prominent applications in optimizing greenhouse climate control [13], reducing food waste [14] and cold chain management to track temperature and humidity conditions during the storage and transportation of perishable goods.

Despite its potential, data privacy concerns, high deployment costs, and a lack of integration between IT and OT due to the gap between these traditionally separate domains hinder the adoption of IIoT in the industry.

1.3. IIoT platforms & research issues in IT/OT integration

IIoT platforms are integral to the realization of IIoT concepts. They are technology solutions (typically software applications) that facilitate the execution of IIoT solutions. These platforms are highly effective, acting as central hubs to aggregate and process data collected from diverse sources, ensuring real-time insights [15]. The key functionalities of IIoT platforms include data collection, connectivity, analytics, and security.

As recognized by Gartner, the IIoT platform market is dominated by major software vendors such as IBM and industrial automation companies such as ABB. According to Gartner, the market definition of Internet of Things (IoT) platform is [16]:

> *An IoT platform is an on-premises software suite or a cloud service (IoT platform as a service [PaaS]) that monitors and may manage and control various types of endpoints, often via applications business units deploy on the platform. The IoT platform usually provides (or provisions) Web-scale infrastructure capabilities to support basic and advanced IoT solutions and digital business operations.*

In manufacturing, an IIoT platform interfaces and pulls live data from equipment while connecting to factory historians or libraries of machine performance [15]. These platforms not only facilitate data integration but also bridge the IT-OT gap by providing holistic insights into industrial processes. However, the adoption of IIoT platforms, particularly in the highly fragmented food industry with small-scale traditional players, poses significant challenges. Lack of standardized data communication protocols, coupled with workforce training and usability issues, often become roadblocks to successful IT/OT integration [11]. Additionally, IIoT adoption also benefits from integration of emerging technologies such as artificial intelligence, edge computing, and 5G networks. In this context, our paper examines the role of IIoT platforms and their intricate implementation challenges from both systems and a socio-technical perspective. Driven by the complexities of IIoT adoption, we pose the following exploratory questions for this paper:

RQ1: How does IIoT platform implementation support food industry goals concerning product traceability and supply chain visibility?

RQ2: What are the design considerations for IIoT platforms to ensure high industry adoption while accounting for IT/OT integration challenges?

This paper primarily focuses on the IIoT platform implementation in a factory setting. Section 2 introduces the data collection methods and the Azure IoT platform case details. Section 3 presents the findings from the analysis tailored to industry needs via the quality function deployment (QFD) method. This is followed by a discussion on design considerations in Section 4. Finally, conclusions are drawn in Section 5.

2. Approach

This paper uses a combination of empirical studies and case study analysis [17]. Drawing from the selective literature on contemporary challenges in the IIoT domain, we identify the research issues in implementing the IIoT platform. To ensure strong research relevance, we synthesize evidence on the specific technological needs of the manufacturing industry. Subsequently, we conduct requirements analysis using the QFD method and utilize Industry 4.0 learning factory for requirements specifications and illustrate our points with the Azure IoT platform as an example. Consequently, we extrapolate design considerations central to the effective implementation of IIoT platforms.

2.1. Primary and secondary data on industry needs

We use the empirical data from two large Danish food manufacturers and triangulate the data using archival documents and industry reports. We use this data to draft specific requirements and challenges and summarize the findings in Table 1. In bold, we highlight the outstanding details of industry needs, which we use to draft the final list of industry requirements.

Table 1 Summary of collected qualitative data

Source	**Primary data from Company A**	**Primary data from Company B** *(to ensure reliability)*	**Secondary data from Industry reports** *(to ensure validity)*
Size (employees)	>10,000	>10,000	-
Industry	Dairy	Meat processing	-
Interviewee	AA	BB	-
Finding 1 Industry needs concerning traceability	To achieve traceability, the company aims to **involve business departments** in shop floor solutions. **Implementing manufacturing execution systems** will enable these departments to become 'solution owners', a shift from the previous approach where only the IT department managed solutions.	Quality control and hygiene inspections are crucial in the fresh food industry. **Using sensor technology** in slaughterhouses can guide workers to achieve traceability for quality and high throughput.	The food industry must implement robust technology-based traceability systems using barcodes and RFID tags (e.g. ear tags on individual livestock) for **more comprehensive data collection.** This enables end-to-end traceability from farm to fork across the value chain to align with consumer and regulatory requirements [18].
Finding 2 Industry needs concerning supply chain visibility	The company is investing to enhance production capacity and footprint, with a digital supply chain focus to maximize data value. Yet, challenges arise due to **data being dispersed across disconnected clouds held by vendors**. The company aims to gain **data ownership**, enabling analysis and vendor flexibility [19].	The company wants **real-time scheduling** and daily factory production planning. As a cooperative of 5,000+ farmers, it's limited to internal suppliers. Their goal is **digital solutions emphasizing global traceability and genealogy** [19]**.**	The need to 'future proof' supply chains to respond to food inflation and geopolitical concerns by reducing inefficiencies due to siloed systems. Freight tracking and **visibility software** and **real-time transportation visibility platforms** (e.g. ERP or TMS) provide live tracking of food locations and their status and product climate control [20].

2.2. The case of Microsoft Azure IoT platform - an illustrative example

We use the Microsoft Azure IoT platform as an illustrative exemplar for this study, considering its recognition by Gartner as one of the leading IIoT platforms in the current market landscape [15]. The Azure IoT platform is a software suite and a cloud-based solution. Its *Azure IoT hub* facilitates two-way communication between IoT applications and the devices they manage. *Azure IoT Central* has the no-code approach and IoT solutions can be quickly created and tailored specific to industry needs. *Azure IoT Edge* enables localized data processing and analytics. Manufacturers can, for example, predict machine failures by availing the predictive maintenance features of *Azure Machine Learning* that integrates with the Azure IoT platform [21]. We illustrate IIoT platform functionality through the Azure IoT example, with its reference architecture illustrated in Figure 2.

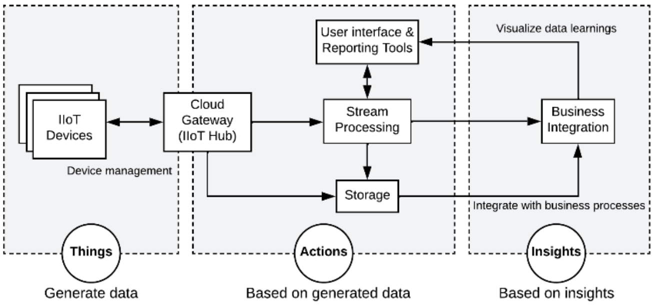


Fig. 2. *Microsoft Azure IoT Reference Architecture, illustrating its core subsystems* [21]

2.3. QFD method for requirements analysis

To link industry requirements and IIoT platform capabilities, we use the QFD methodology, a well-established research technique in the engineering field that bridges the gap between desired outcomes and technology offerings (See Fig. 3). QFD has its origins in Japan during the late 60's. With this approach and its *House of Quality* tool, we meticulously evaluate various IIoT platform functionalities to analyze their alignment with the industry demands, in our case, the food industry's needs pertaining to product traceability and supply chain visibility. Our chosen exemplar, Azure IoT platform, serves as a tangible case to distill design considerations.

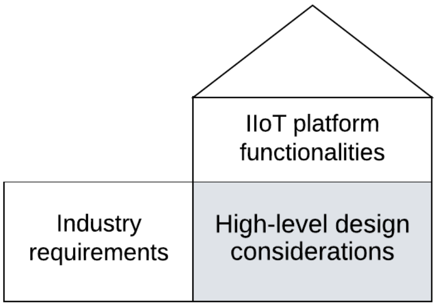


Fig. 3. *QFD House of Quality for determining design considerations*

2.4. 'The Smart Lab' for requirements specification

We use Aalborg University's Smart Production lab (The Smart Lab), which is a 'small Industry 4.0' learning factory in Denmark [22], as part of our methodology as a backdrop to discuss design considerations. The lab is a cyber-physical production system with advanced IT architecture that captures Industry 4.0 concepts (see Fig. 4). The lab serves as a playground for research experimentation, and its fully automated discrete assembly line includes [11]:

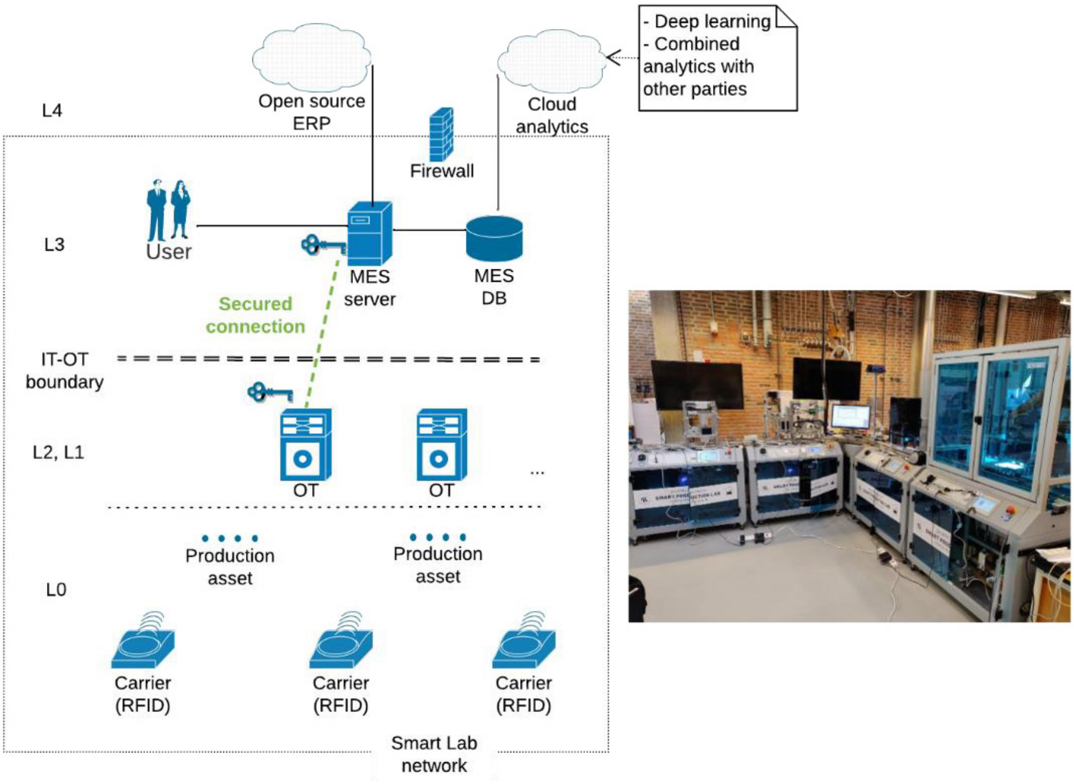


Fig. 4. *The high-level architecture of Smart Lab, an Industry 4.0 learning factory*

- Five production modules, each housing a pair of stations;
- Manufacturing execution systems (MES) installed on a single computer orchestrating overall production through high-level process control;
- Festo CECC-LK programmable logic controllers (PLCs) on each station;
- Network connectivity through ethernet cables interlinking the PLCs and MES computer with an option for wireless operations through Wireless Multi-Access Gateways.

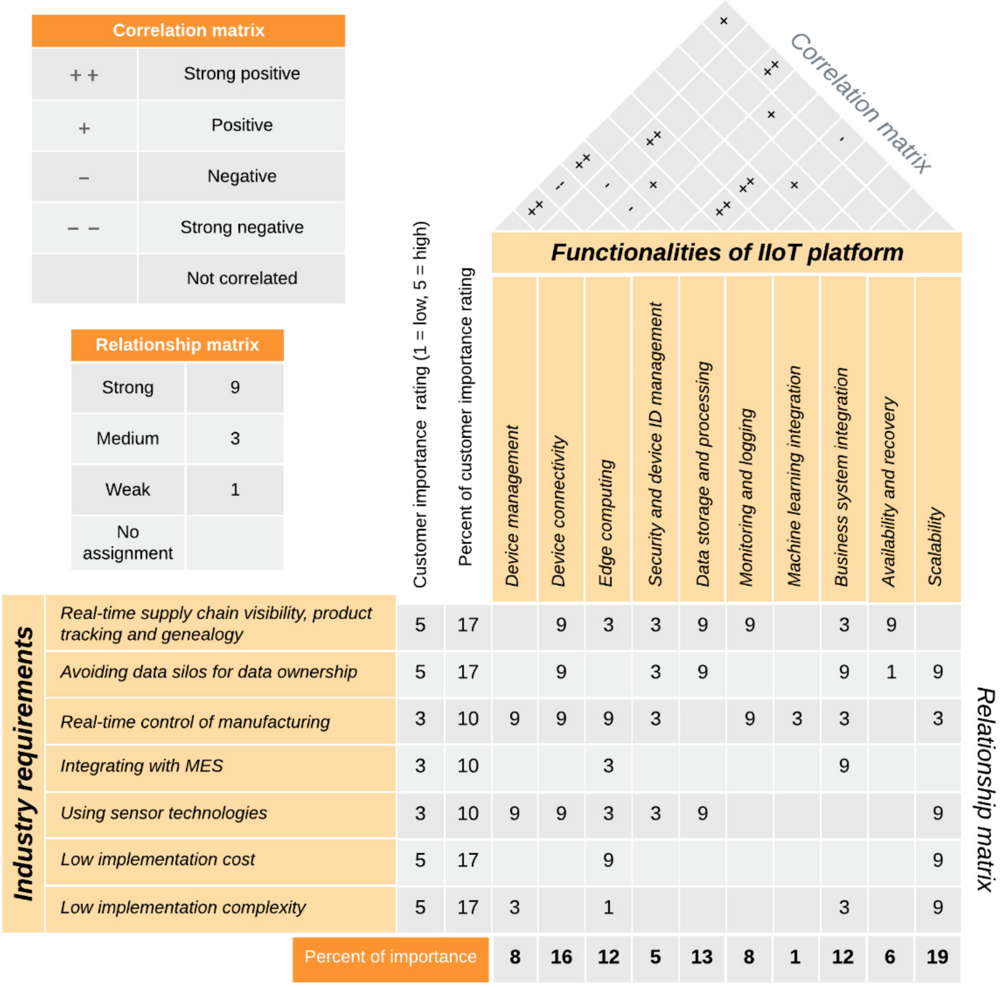
3. Findings

In this section, we present the findings from the QFD analysis (see Fig. 5), where the IIoT platform functionalities based on Azure IoT are:

- **Device management**: Provides tools for registering, configuring, and managing IoT devices
- **Device connectivity**: Facilities and interfaces the links between IIoT devices and the platform through cloud gateways and, potentially, field gateways at the edge
- **Edge computing**: Enables on-premise data processing and device control for reduced latency, higher security, and reduced load on data transfer to the cloud
- **Security and device identity management**: Stores device identity information and cryptographic secrets for device authentication
- **Data storage and processing**: Offers scalable cloud data storage and functionalities for both real-time and batch data processing and analytics
- **Monitoring and logging**: Allows monitoring of the status and health of IIoT devices, aiding in identifying and troubleshooting the problems with device operations
- **Machine learning integration**: Provides at-rest analysis of IIoT data for advanced analytics, anomaly detection, and predictive maintenance
- **Business system integration**: Allows integration with downstream business systems such as enterprise resource planning (ERP) and MES
- **Availability and recovery**: Ensure that the IIoT system has near-zero downtime and swift recovery from potential failures, for example, through redundant systems
- **Scalability**: Allows scaling the IIoT solution to large numbers of devices, potentially distributed across different global locations of a manufacturing supply chain

Our QFD analysis is informed by seven customer requirements based on the qualitative data analysis (see 2.1), rated for importance on a scale of 1 to 5. Four are highly important, as they are non-negotiable within the industry. Due to their specific technological characteristics, the other three are rated as medium importance. Based on these scores, we derive the percentages of customer importance ratings.

The roof shows the correlation between different functionalities. For example, a strong positive (++) case where *Scalability* and *Edge computing* strongly complement



Correlation matrix	
+ +	Strong positive
+	Positive
–	Negative
– –	Strong negative
	Not correlated

Relationship matrix	
Strong	9
Medium	3
Weak	1
No assignment	

Industry requirements	Customer importance rating (1 = low, 5 = high)	Percent of customer importance rating	Device management	Device connectivity	Edge computing	Security and device ID management	Data storage and processing	Monitoring and logging	Machine learning integration	Business system integration	Availability and recovery	Scalability
Real-time supply chain visibility, product tracking and genealogy	5	17		9	3	3	9	9		3	9	
Avoiding data silos for data ownership	5	17		9		3	9			9	1	9
Real-time control of manufacturing	3	10	9	9	9	3		9	3	3		3
Integrating with MES	3	10			3					9		
Using sensor technologies	3	10	9	9	3	3	9					9
Low implementation cost	5	17			9							9
Low implementation complexity	5	17	3		1					3		9
Percent of importance			**8**	**16**	**12**	**5**	**13**	**8**	**1**	**12**	**6**	**19**

***Fig. 5.** The House of Quality – linking industry requirements with IIoT platform functionalities in Industry 4.0*

each other by moving some of the manufacturing data processing to the edge to lower the computational and bandwidth burden on the IIoT cloud platform. In a positive (+) score, *Monitoring* and *Business system integration* reinforce each other by allowing monitoring from shop floor devices and business systems such as MES to be done in a central location. In a strong negative (--), *Edge computing* conflicts strongly with device management since a central server no longer manages the IIoT devices.

Although a QFD matrix is self-explanatory, we discuss the rows of the house individually to provide our reasoning for the scores given to selected cells in the house:

- **Real-time supply chain visibility, product tracking, and genealogy**: *Device connectivity*, *Data storage and processing*, *Monitoring and logging*, and *Availability and recovery* emerge as critical requirements, supplemented by functionalities such as edge computing. Supply chain visibility depends fundamentally on data extraction from devices across different supply chain stages, as well as the analysis and presentation of the data.
- **Avoiding data silos for data ownership**: Business system integration fosters unified data analysis from different departments of the company, collecting data and insights from IIoT and other value chain components (e.g. consumer data).
- **Real-time control of manufacturing**: Most IIoT platform functionalities directly support this requirement. For example, monitoring device health and reporting performed operations through logging at a cell level in the production line is a prerequisite for efficiently controlling the manufacturing process. In the Smart Lab, every time the carriage brings the product to a station for an operation to be performed (e.g. drilling), the PLC of the station reports details of the performed operation to the IIoT platform. This enables the platform to take action to control the manufacturing process, if necessary.
- **Integrating with MES**: A direct example of *Business system integration*.
- **Using sensor technologies**: Many IIoT platform functionalities support the use of sensor technologies since sensors are some of the most common forms of IIoT devices. *Data storage and processing* is essential for utilizing the data reported by sensors.
- **Low implementation cost**: Edge computing can mitigate implementation costs by facilitating less computationally powerful IIoT devices that need not be capable of securely connecting to the cloud themselves.

- **Low implementation complexity**: A scalable IIoT platform architecture eases implementation across diverse systems since the same design can be used for both small and large IIoT systems, and no profound architectural changes are needed when the system is scaled up.

We attain the highest percentages of importance for *Scalability* (19%) *and Device connectivity* (16%). In food supply chains, high scalability denotes the ability of the IIoT system to expand to include numerous farms, warehouses, processing plants, transportation vehicles, etc., while also enabling the extraction of more detailed data from each of these areas.

4. Discussion

Previous research on IIoT implementation predominantly concentrated on IIoT architectures and design principles [7], with limited attention to their adoption and integration challenges within the existing IT/OT landscape in brownfield manufacturing environments, especially their alignment with ISA 95 structure. Brownfield factories inherit legacy systems and already follow some ISA 95 principles. They may not be ready to rip and replace their pre-existing systems with a new IIoT platform. Therefore, implementing a platform that complements the existing systems must be a foremost design priority. Industrial automation standards such as ISA 95 retain relevance in Industry 4.0 by offering data models and flows for information exchange and reducing vendor lock-in. Standardization supports scalability and interoperability, ultimately reducing long-term costs. Hence, our findings contribute to a reliable and future-oriented enterprise architecture that is flexible and easy to maintain.

4.1. Considerations for IT/OT integration

Modern IT infrastructure must consider the complexities of interconnecting with legacy OT systems, and some of the solutions to this problem can be found in open-source solutions, open standards, protocol gateways, application programming interfaces, and middleware. These solutions facilitate data exchange and communication between disperate systems.

IIoT platform integration with existing ISA 95-based systems: Figure 6 presents the class diagram of high-level system architecture of a factory with the IIoT platform depicted in Unified Modeling Language (UML). This diagram depicts entities, relationships, and the integration of an IIoT platform with ISA 95, using the Azure IoT and the

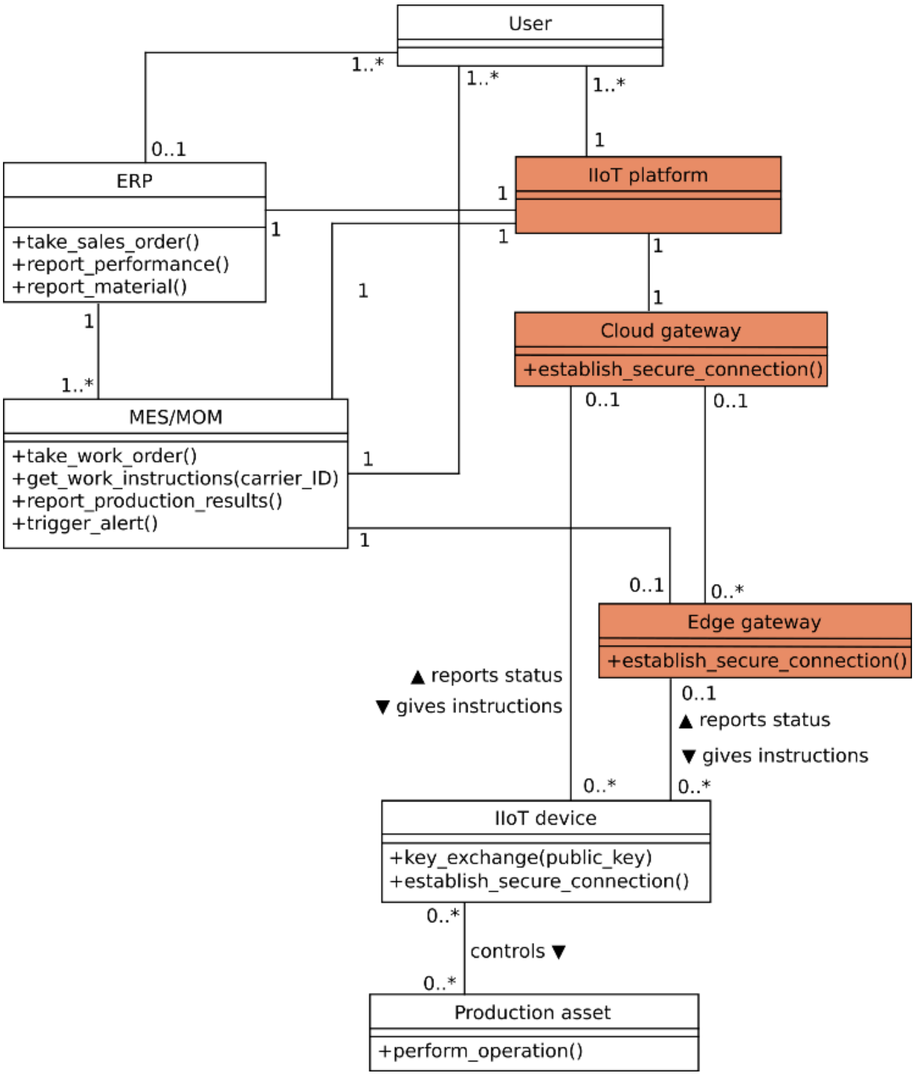


Fig. 6. *UML class diagram of the proposed high-level architecture of a factory with IIoT platform*

'Smart Lab' scenario as an example. Here the IIoT devices connect with either Cloud or Edge gateways [21]. If MES is deployed locally in the shop floor network, it connects directly with the Edge gateway.

Although IIoT platforms enhance connectivity, they have cybersecurity challenges and require robust measures and risk mitigation strategies. The future impact of IIoT on industries is significant, including improved connectivity, real-time data-driven decision-making, and new business models.

We have addressed **RQ1** by verifying the relevance of IIoT functionalities for food industry-specific requirements, and our findings indicate a strong correlation between IIoT platforms and product traceability and supply chain visibility needs. By analyzing the findings from the QFD analysis, we answer **RQ2** using Figure 6 to present the system architecture design considerations (based on Smart Lab's architecture example) for implementing an IIoT platform while facilitating IT/OT integration.

4.2. Future work

This initial study is the first iteration that explores the application of the IIoT platform and its future implementation strategies. Future work will conduct an exhaustive in-depth case studies in companies to follow their IIoT implementation journey and challenges, followed by lab-based experimentation to propose design enhancements to contribute to the theories on IIoT system design principles.

Research into standardization is essential and must consider industry best practices. Organizations such as RAMI, Industrial Internet Consortium (IIC) and the OPC Foundation are pivotal in developing open industrial standards to enable modular and cost-effective IIoT ecosystems.

Empowering the food industry: This paper uses traceability and supply chain visibility, highly relevant to the problems with industrial food systems, to ensure the manufacture and supply of safe and affordable food products. We expect the industry to utilize the principles discussed in this paper to create IIoT solutions tailored to their individual needs by using our QFD template. More empirical studies are needed to examine IIoT platform implementation in companies, especially in food systems with diverse stakeholders. Distributed computing paradigms such as blockchains are gaining traction, particularly in ensuring supply chain transparency and addressing food safety concerns. IIoT platforms can serve as effective data collection tools for blockchain implementation [23].

Using case-based approaches is the way forward to studying the unresolved challenges of IIoT. While we used the Azure IoT platform as an example, small-scale companies with budget constraints can explore developing homegrown solutions based on the discussed functionalities and design.

5. Conclusions

Manufacturing enterprises are interested in implementing IIoT platforms for their Industry 4.0-based data management initiatives to meet the ever-evolving market demands. Therefore, we attempted to understand the usage and design considerations of IIoT platforms for optimal industry integration. Focusing on the food sector as a case study, we explored how IIoT platforms can support traceability and supply chain visibility goals. These platforms provide data-driven insights for operational enhancements to empower food systems to ensure food safety, distribution, and affordability. These empirical findings guide future research and advancements, making the food industry more organized and efficient.

Our study focused on IIoT implementation within the factory environment, utilizing Microsoft Azure IoT as an illustrative example. Through the Quality Function Deployment (QFD) analysis, we explored the interplay of various IIoT platform components and functionality. Based on this nuanced analysis, we also discussed design considerations to refine the connectivity and integration of systems within a factory. The proposed high-level factory system architecture (see Fig. 6) presents IIoT platform housed in ISA 95-based structure, complementing the manufacturing execution systems. This design emphasized the critical role of IT/OT integration for a successful IIoT platform implementation and adoption (and vice versa). We deduce that this integration for efficient and secure data exchange and process control requires a socio-technical approach to bridge the digital and physical worlds of manufacturing.

The paper is a starting point for understanding how IIoT platforms can be implemented and tailored for individual company and industry needs. Future work will perform in-depth case studies for requirements analysis and add more complexities to the proposed design. As far as we know, this is the first time IIoT platform functionalities have been analyzed for their effectiveness for specific industry requirements using a QFD method.

We attained the highest percentages of importance for ***Scalability*** (19%) and ***Device connectivity*** (16%) functionalities; therefore, conclude that any company with IIoT platform implementations must pay special attention to these core functionalities. Although our QFD analysis assigned a lower score to *Security and device ID management*, since it is not captured well by our chosen industry requirements, we stress that it is an essential feature of an IIoT platform to avoid data theft and disruption of the business processes by malicious actors. Therefore, cyber security should lie at the heart of any IIoT platform's integrity.

6. Abbreviations

CoAP: Constrained Application Protocol
ERP: Enterprise Resource Planning
IIoT: Industrial Internet of Things
IoT: Internet of Things
ISA: International Society of Automation
ISA 95: An international industrial automation standard
IT: Information Technology
MES: Manufacturing Execution Systems
MQTT: Message Queuing Telemetry Transport
OPC UA: Open Platform Communications Unified Architecture
OT: Operational Technology
PaaS: Platform as a Service
PLC: Programmable Logic Controller
QFD: Quality Function Deployment
RAMI: Reference Architectural Model Industrie 4.0
RFID: Radio Frequency Identification
TMS: Transportation Management System
UML: Unified Modeling Language

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