Department of Industrial Engineering & Maintenance

Intelligent Manufacturing Execution Systems in the Food and Beverage Industry

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Master's thesis in Industrial Engineering (GI)

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Abstract: Manufacturing Execution Systems (MES) emerged as a software solution to bridge the gap in digital communication between two functional layers: the company's management and the supervisory system. Initially focused on tracking and operational control, MES has evolved through the integration of Artificial Intelligence (AI), the Internet of Things (IoT), and Big Data Analytics (BDA), leading to the emergence of Intelligent Manufacturing Execution Systems (IMES), which satisfy Industry 4.0 requirements.

Advanced technologies have driven industries toward digitalization, particularly within the Food and Beverage (FB) sector. This industry faces demands for traceability, compliance, agility, and sustainability, necessitating flexible, real-time solutions that traditional systems cannot provide. The digitalization of the FB sector has been propelled by the integration of advanced technologies into intelligent MES platforms, which provide the capabilities necessary to meet modern industry demands.

To demonstrate these statements, we described eight case studies from the dairy, meat, dietary supplement, brewing, and beverage manufacturing sectors. The final case study, which we focus on and conducted at ECCBC, is detailed to illustrate the successful implementation of IMES, which has automated monitoring, reduced waste, and improved responsiveness to consumers' needs.

This paper analyzes the evolution of MES into intelligent platforms within the context of digital transformation in the food and beverage industry. It describes the critical role of IMES in enabling innovative, sustainable, and flexible manufacturing environments. It also addresses several implementation challenges, including system integration, technology complexity, and organizational readiness. The findings support the strategic positioning of IMES as a key enabler of next-generation manufacturing systems aligned with Industry 4.0 objectives.

Key-Words: Intelligent Manufacturing Execution System, Smart Factory, Advanced Technologies, Industry 4.0, Food and Beverage Industry, Production Optimization, Operational Efficiency, Digital Transformation.

Contents

1. Introduction

MES acts as a crucial link between enterprise-level planning systems, like ERP (Enterprise Resource Planning), and shop floor operations, such as PLC (Programmable Logic Controller) and SCADA (Supervisory Control and Data Acquisition), addressing gaps in real-time data integration and bidirectional communication [1][2]. Manufacturing Execution Systems (MES) have historically focused on tracking and operational control. Over time, MES has gradually integrated advanced technologies such as artificial intelligence, the Internet of Things, and Big Data Analytics. These developments have led to Integrated Manufacturing Execution Systems (IMES), which provide real-time visibility, predictive capabilities, and adaptive responses to production variability [1][3][4][5].
The global MES market is projected to grow from 12.47 billion dollar in 2022 to 36.9 billion dollar by 2032, highlighting the demand linked to the strategic importance of scalable, intelligent solutions for modern manufacturing [6].
In this race toward intelligent production, the food and beverage industry—a sector long seen as traditional and process-driven—is experiencing a significant transformation. The rising demand for traceability, regulatory compliance, agility, and sustainability has revealed the limitations of conventional production systems, opening up opportunities for flexible, real-time solutions [7]. At the core of this shift are MES, digital platforms designed to manage, monitor, and optimize shop floor operations. Since their introduction, these systems have undergone a significant transformation, evolving from static data collection tools into dynamic systems that enable informed decision-making.
Today, this development is being accelerated with the advent of IMES, which has been significantly enhanced by the emergence of advanced technologies, including artificial intelligence, the Internet of Things, and big data analytics, to improve both efficiency and responsiveness in manufacturing [1][3].
Before delving deeper into the paper's content, it is essential to address the existing knowledge gaps and limitations of previous research on MES and its evolution toward Intelligent MES, particularly within the Industry 4.0 framework and the food and beverage sector [8].
Despite increasing academic attention, the literature remains fragmented and outdated, with a noticeable lack of understanding regarding the specific requirements and operational particularities of the food and beverage industry [7][9][10], which is evident in existing studies that typically fall into four broad categories: overviews of MES, studies on the emergence of advanced technologies within MES to achieve intelligent capabilities, implementation approaches, and case study applications. However, each of these categories reveals significant limitations in addressing challenges and success factors relevant to real-world industrial contexts [11]. Traditional overviews often present generalized functions without adapting to food and beverage-specific constraints, such as perishability, hygiene compliance, and sustainability goals [9][10]. Research on emerging technologies tends to emphasize theoretical models rather than validated, practical integration [3]. Implementation approaches frequently overlook the context of SMEs and the complexity of deployment in resource-constrained environments [12][11]. Additionally, case studies are commonly simulation-based, providing limited empirical insight into the technical and organizational realities of IMES adoption [1]. These persistent gaps highlight the necessity for an updated, sector-specific framework that accounts for technological, economic, and regulatory dimensions. This study contributes by offering a comprehensive and empirically grounded investigation that addresses these deficiencies and supports the effective deployment of IMES in the food and beverage sector. While many companies already have a Manufacturing Execution System (MES) in place, few take advantage of the additional intelligent layer that can turn these systems into active decision-making tools. A central question this article will address is:

How can the food and beverage industry leverage IMES in its operations and strategy to tackle the evolving challenges of a rapidly digitized world?

The paper employs an integrated research methodology to explore the adoption of Manufacturing Execution Systems in the food and beverage industry. It utilizes data from various databases, including Scopus, HAL, Elsevier, ResearchGate, Procedia Manufacturing, and IEEE, to analyze publication trends and contributions from authors in the field.
The paper aims to investigate the integration and impact of MES within the context of Industry 4.0, focusing on how MES evolves with advancements in automation, reconfigurability, and real-time decision-making in smart factories. It also examines the specific challenges and benefits of MES implementation in the food and beverage sector, discusses the adoption of MES by small and medium-sized enterprises (SMEs), and proposes methodologies for successful digital transformation. The findings are supported by practical applications and case studies, drawing on 42 references to substantiate the analysis.
This article begins with a foundational overview of MES and traces its evolution. It then examines the enabling technologies that power IMES, followed by illustrative case studies. The discussion section presents a critical analysis of the success factors, challenges, and strategic implications of these systems, highlighting the potential that IMES represents as a significant step into another industrial age in food and beverage manufacturing, characterized by data and speed as its defining traits.

2. Overview of Manufacturing Execution Systems

This section offers a comprehensive analysis of IMES, detailing its definition, evolution, and integration within the framework of Industry 4.0.

2.1. Definition of MES

In terms of manufacturing competitiveness, industrial companies strive to utilize advanced techniques that enhance efficiency, improve quality, and achieve greater flexibility and sustainability. Modern industries are guided by the Industry 4.0 vision to achieve high levels of digital capabilities to tackle the challenges of transformation, such as interconnectivity, managing big data, integrating real-time information, and ensuring adaptability among smart factories, IT infrastructure, and software [3]. In most smart factories, there are two types of software:

- The company's management system generally consists of an ERP and a CAPM (Computer Aided Production Management) [2].
- The supervision system provides real-time control of production resources, such as PLC and SCADA.

Figure1 illustrates the connections between these systems and the flow of information among them. It highlights their distinct time frames, decision-making levels, and how the details and scope of the shared information evolve as one progresses through the layers.

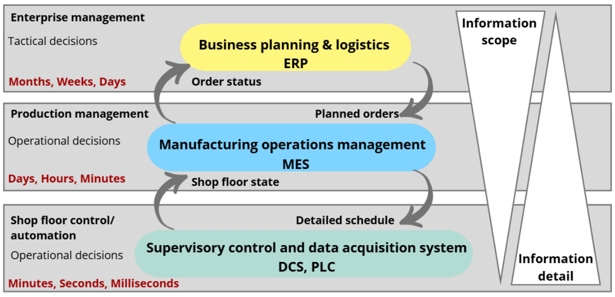

Figure 1: Information and management systems for planning and control [1]

The MES emerged from the need for digital communication between these two functional layers, ensuring alignment and synchronization. It also serves as a bidirectional link between enterprise planning and the shop floor, encompassing control and automation systems [1]. It typically resides at the third level of the CIM (Computer Integrated Manufacturing) automation pyramid (Figure 2).

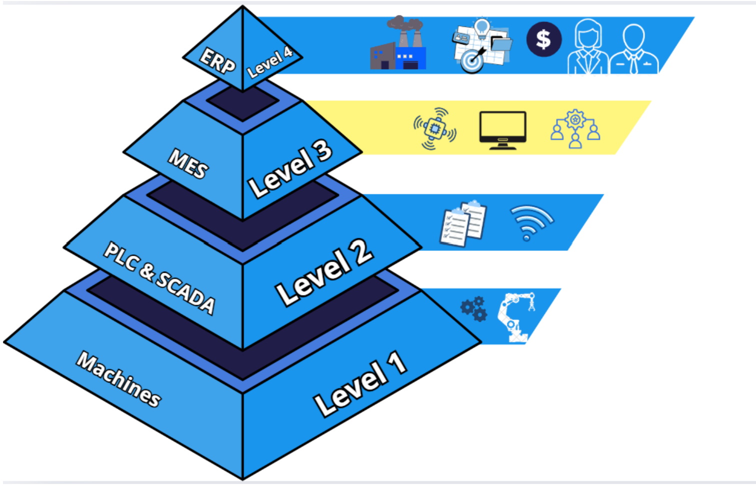

Figure 2: CIM automation pyramid

MES has evolved from basic tracking systems to process-centric software solutions that collect and manage real-time information from manufacturing processes [3][4]. This enables real-time management of shop floor activities by utilizing manufacturing information about equipment, resources, and orders to optimize production [3]. It has evolved, incorporating extensions to perform manufacturing activities through advancements in information technology. The core function of an MES is to provide accurate information about the actual status of the production system, along with analytical tools to enhance both the quantitative and qualitative aspects of production [7].

2.2. Emergence and Evolution of MES

When MES first appeared in the 1970s, its main objective was to support production execution, focusing on online shop floor activity management. The development of MES closely relates to manufacturing strategies that emphasize cost reduction and the integration of planning and process control. This development involved multiple stages, including MRP, MRPII, computer-aided manufacturing, and ERP systems, aimed at enhancing production efficiency and competitiveness [1] [3][7]. The need for data integration from various sources, including shop floor and enterprise systems, along with the requirement to manage the increasing complexity of manufacturing processes, has propelled the growth of MES. SMEs are rapidly transitioning to more reliable and efficient alternatives to the paper-based solutions they previously depended on [13]. Fueled by advanced technologies, Industry 4.0 signifies a major transformation in the industrial landscape. Therefore, to support the upcoming generation of production systems, digitizing MES is crucial [3] [14].

Table 1: Comparison between Traditional MES and Intelligent MES - Source: Author's work

Characteristic	Traditional MES	Intelligent MES
Main Objective	Simplify production execution and link planning (ERP) with control systems (PLC, sensors).	Maximize production data for continuous improvement and optimization with big data analytics.
Data Management	Collect and store production data, primarily used for performance indicator calculation.	Real-time management and analysis of massive, diverse data from various sources using big data analytics to extract insights.
Analysis and Decision	Performance indicator calculation (such as OEE) with limited diagnostic support, relying on human expertise.	Real-time visibility and performance analysis with advanced diagnostic support, enabling fast and intelligent decision making at all levels.
Intelligence and Autonomy	Reactive and rule-based, relying on human expertise.	Autonomous and intelligent operations with AI and ML for maintenance, detection, optimization, and decision making.
Integration	Interoperability through integration with ERP, PLM (Product Lifecycle Management), and traceability systems, following the ISA-95 standard.	Fast and secure integration with a broad ecosystem of systems and devices, enabling vertical integration within Industry 4.0.
Diagnosis	Limited and predefined failure diagnosis with minimal analysis of performance and quality issues.	Advanced diagnostic capabilities using probabilistic models to identify performance deviation causes.
Reactivity	Reactivity based on configured information and alerts.	Real-time responsiveness through continuous data analysis.

MES has transformed from basic tracking systems to advanced integrated solutions. An IMES represents an evolution of traditional production systems, incorporating cutting-edge technologies to enhance real-time processes. Using standards like ISA-95 and OPC UA (Object Linking and Embedding for Process Control) [2], it also integrates with various systems, including ERPs and automated control systems, providing an integrated view of industrial activities [15]. To better understand the evolution from traditional to intelligent MES, (Table1) highlights the main differences between these two generations of systems. It facilitates a comparison of their primary objectives, data management, analysis, decision-making, intelligence, autonomy, as well as their integration, diagnosis, and reactivity. Traditional MES focuses on production execution by ensuring the connection between ERP systems and shop floor control devices, such as PLCs and sensors. With limited diagnostic capabilities and a reactive approach based on human expertise, it collects and stores production data to compute performance indicators like Overall Equipment Effectiveness (OEE). However, the IMES employs big data analytics to manage and analyze large volumes of real-time data from various sources, facilitating vertical integration with Industry 4.0. This enables intuitive system and device integration, autonomous decision-making, and advanced diagnostics. Additionally, it enhances diagnostics and flexibility by utilizing continuous data analysis and probabilistic models.

3. Technologies and Features of IMES

IMES are characterized by the integration of advanced Industry 4.0 technologies, notably Artificial Intelligence (AI), the Internet of Things (IoT), Machine Learning (ML), and Big Data Analytics (BDA). This section presents these technologies, their integration into MES, and the resulting features of this integration (Figure 3).

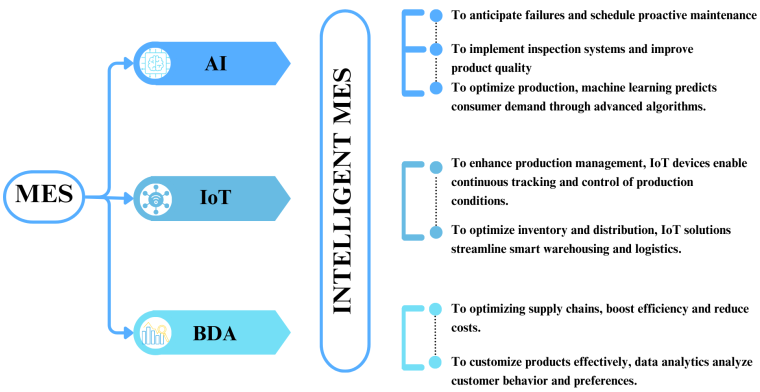

Figure 3: Technologies and Features of IMES
Source: Author's work

3.1. Integration of MES with AI

AI is a field of computer science that develops systems capable of performing tasks typically requiring human intelligence. It encompasses key elements summarized by the acronym ABCDE: Analytics technology, Big Data, Cloud Computing, Domain knowledge, and Evidence [16]. Integrating AI into MES can significantly improve manufacturing operations. It involves understanding the problem, the available data, the physical meaning of parameters, the characteristics of a manufacturing process, and the uncertainties associated with the parameters. This explains why the integration of AI enhances IMES. Thus, feedback on real-world models improves the accuracy of AI models [1]. In manufacturing companies, where devices essentially monitor operations, AI is being used increasingly. It is applied for reasoning, knowledge, planning, learning, natural language processing, and perception [**?**]. AI enhances this capability by powering systems that imitate human behavior and operate in areas such as planning and decision-making, thereby advancing predictive maintenance, real-time monitoring of production conditions, and quality control [1][17][18][19].

For predictive maintenance, as the IT center of factories, IMES collects and manages vast amounts of real-time production data. This data originates from machines, sensors, controllers, and automatic identification systems. Integrating AI allows for the analysis of this data to establish failure models through data correlations, known as Data Mining, which can indicate potential equipment failures [1]. The combination of AI and ML with MES will enable predictive analytics and advanced process optimization, further enhancing the benefits of IMES [19][20]. Additionally, the integration of AI techniques with the Digital Twin—a virtual copy of a physical system used for simulation, monitoring, and diagnostics—enables the prediction of equipment failures and the optimization of maintenance by simulating realistic future scenarios [**?**][21]. However, some sources note that applying ML to the design of predictive maintenance applications is still a relatively new approach, with a lack of improvement in equipment detection methods to enhance data quality and quantity. In addition, existing IMES models for Industry 4.0 do not sufficiently emphasize the inclusion of predictive maintenance[1][21]. For example, in a predictive maintenance setup, AI within a MES uses historical operations data such as error messages, cycle times, and power consumption to train an ML algorithm to identify subtle trends and anomalies that indicate upcoming equipment failures. Once the AI detects these early anomalies, it generates predictive alerts that prompt the IMES to automatically schedule maintenance during planned downtimes; consequently, this prevents unexpected breakdowns, reduces repair costs, and extends the life of the equipment [**?**]. **For intelligent quality control through image recognition**, a powerful application that aims to significantly improve product quality, the integration of AI-driven industrial vision systems within MES automates and enhances the accuracy of visual inspections, thus contributing to better quality assurance [1]. As previously mentioned, IMES enables the collection and management of real-time production data. Image recognition and machine learning techniques can be applied to these data streams to automatically identify defects and anomalies that may go unnoticed during human inspections [1]. AI-driven industrial vision systems can be trained to recognize various types of product defects. They facilitate continuous quality monitoring, ensuring early defect detection and quick intervention to prevent defective batches [13]. Moreover, they simplify root cause analysis by maintaining inspection records [4]. AI can assist in identifying correlations between defects and production parameters, enabling more effective corrective actions. Automating inspections reduces subjectivity and human errors, while linking inspection results to traceability information ensures accurate tracking and effective recall management [7][15]. A key element of the IMES concept that stems from more intelligence is quality [1]. The integration of AI for quality control in IMES aligns with a broader trend toward smart factories, where machines and products communicate and make autonomous decisions to optimize production, including quality [15]. For example, a quality control process supported by AI uses high-resolution cameras to capture images of the production line. These images are then processed in real-time. The system identifies anomalies indicating nonconformity, automatically detects defective products, and instantly interacts with the IMES to activate corrective actions, such as stopping the line or adjusting production parameters. This automated visual inspection reduces dependence on manual controls, decreases variability, and minimizes waste [1][7][17].

For demand forecasting, ML seeks to optimize production planning by anticipating consumer needs. With the incorporation of ML algorithms into MES, companies can achieve more accurate demand forecasts and adjust their production operations accordingly [1]. Essential information for demand forecasting includes sales and order history, inventory levels, current and past production data, equipment performance information, and external data such as market trends, promotions, and supply chain information [17]. ML algorithms can be applied to the vast datasets collected by IMES to identify patterns, trends, and correlations that help predict future consumer demand [15][17][20]. Accurate demand forecasts obtained through IMES enable optimization of the production schedule [1][22], allowing for flexible adjustments to production plans in order to effectively respond to fluctuations in demand. For example, the system can automatically adjust manufacturing orders, distribute resources effectively, and modify work schedules in connection with predicted periods of high demand [19]. This adaptability also supports the optimization of inventory levels by ensuring that the correct quantity of products is produced at the right time, thereby minimizing storage costs and reducing the risk of stockouts. Additionally, it enhances resource utilization by enabling optimal planning of machines, labor, and raw materials based on projected demand [1][19]. As a result, delivery times are shortened due to proactive scheduling, and decision-making regarding raw material procurement and capacity planning becomes more intelligent, as insights into future demand allow for better anticipation of upstream supply chain requirements [22].

3.2. Integration of MES with IoT

The IoT enables real-time data collection to monitor and control processes for improvement by allowing various machines, methods, and products to communicate, facilitating their interaction with the cloud for efficient data processing[18][20][23].

For real-time monitoring, integrating the IoT into MES allows for the continuous tracking and management of production parameters [19]. The combination of IoT and MES can lead to several outcomes in the manufacturing environment. IoT devices enable the automated collection of real-time data from the shop floor, providing a continuous stream of valuable information [3]. Sensors and RFID (Radio Frequency Identification) tags are used to track equipment status and stock levels, while IMES records the complete history of batches, orders, and equipment, optimizing flow localization through automatic identification technologies. The integration of IoT allows raw data to be used to assess production performance and equipment efficiency, while resource control is optimized through IMES [13][17][22][24]. These IoT-generated data can be presented through graphical interfaces to enhance collaboration within the factory [25], while also enabling the integration of operational technology with IT infrastructure and ensuring IoT compatibility between computing components [3][16]. In addition, cloud computing allows for quick communication within the network, thereby enabling real-time decision-making [16].

For innovative warehousing and logistics, logistics encompasses the entire flow of products, from the supply of raw materials to the storage, transport, and distribution of the final products. Throughout the supply chain, sensors and RFID technology track the location and condition of products, enhancing visibility and enabling real-time monitoring. These technologies facilitate GPS tracking and remote [25] location both indoors and outdoors when combined with cloud-based systems. To optimize freight transportation, IoT is employed to identify the most efficient routes while ensuring safety, product quality, and faster deliveries [22][26].

3.3. Integration of MES with BDA

BDA involves applying computational and analytical power to process large and diverse datasets, often in real time. To provide helpful information for decision-making, it allows systematic collection and analysis of data [17][27]. Based on AI and ML, BDA plays a key role in optimizing processes and enabling automatic adjustments to production parameters [16]. The integration of BDA into MES fully utilizes the potential of Industry 4.0 by transforming massive volumes of production data into actionable insights for continuous improvement and strategic decision-making [15][19][28].

For supply chain optimization, IMES plays a key role by leveraging the power of BDA and advanced technologies such as IoT, AI, and cloud computing. It provides real-time visibility into inventory levels, machine performance, and production delays, enabling ideal coordination between supply chain management (SCM) and ERP systems by collecting and analyzing vast amounts of manufacturing data [19][26][29]. The IMES supports rational decision-making, identifies trends related to production efficiency, product quality, and customer preferences [22]. This data-driven approach also simplifies optimization planning, allowing for precise adjustments to production schedules and resource allocation based on anticipated demand [4][7]. Furthermore, the system's real-time monitoring capabilities ensure quick responsiveness to disruptions, helping to detect and resolve issues before they escalate [13]. The IMES also enhances product quality and traceability by tracking all information related to the production process and enabling fast corrective actions when needed. Additionally, the integration of predictive maintenance minimizes equipment downtime by anticipating failures through real-time machine data analysis. Finally, the IMES promotes collaboration and integration across the supply chain by acting as a centralized information core, connecting various organizational levels and external partners. As a result, IMES enhances the supply chain by improving efficiency, resilience, and key performance indicators, meeting Industry 4.0 requirements [15][19][30].

For customer behavior analysis, MES utilizing BDA and advanced technologies analyzes customer data and continuously adjusts product features to enhance customer satisfaction. Such success is achieved through optimized order management and supply chain planning, ensuring timely delivery and alignment with consumer demands [31]. Advanced sales forecasting, powered by sensors and analytics tools, enables innovations such as smart shelves that pave the way for personalized advertising based on customer characteristics and behavior. These intelligent shelves optimize inventory control and operational efficiency in addition to improving restocking procedures. Then, the IMES can identify the most profitable customer segments, allowing companies to adapt their strategies to better serve high-value clients while maximizing overall profitability. This integration of data-driven model insights and intelligent systems ensures a competitive edge in meeting evolving market expectations and enhancing customer loyalty [3][22][32].

3.4. More IMES solutions: Complementary Enabling Technologies

While AI, BDA, and IoT form the technological foundation, the true power of IMES emerges from their integration with complementary Industry 4.0 innovations within MES. These include:

- **Cyber Physical Systems (CPS):** allows smart factories by integrating cyber capabilities with physical systems. IMES integrates CPS components (machines, sensors, and more) for continuous communication, decision making, and process control [17][33].

- **Cloud Computing (CC):** Cloud platforms enable data sharing and process monitoring across supply chains. To improve automation and benefit access to real-time production data, IMES applies cloud-based solutions [1].

- **Additive Manufacturing:** IMES supports flexible production by integrating 3D printing for on demand manufacturing and quick prototyping [17].

- **Augmented Reality (AR):** enhances IMES functionality by providing operators with real-time assembly or repair instructions, improving human-machine interaction [1].

- **Simulation and Digital Twins:** create virtual replicas of physical systems, feeding real-time data to IMES. This enables predictive maintenance, optimization, and anomaly detection [1][34].

- **Autonomous Robots (Cobots):** IMES manages human-robot collaboration, ensuring safe and efficient integration of autonomous systems into production workflows [1].

- **Cybersecurity:** IMES relies on reliable cybersecurity measures to protect interconnected systems and ensure secure communication between machines and processes [15].

- **Machine-to-Machine Communication (M2M):** networks enable direct communication between machines, improving operational efficiency. IMES uses M2M data to make decisions in real time [20].

- RFID Technology: RFID tags provide real-time tracking and traceability of resources, enhancing IMES accuracy and reducing production delays [13][15].

- **Industrial Communication Protocols (OPC-UA, Fieldbus):** IMES uses protocols like OPC-UA to collect and transfer production data, ensuring interoperability between IT and OT systems [17].

- **Neural Networks Fuzzy Logic:** IMES employs AI tools like neural networks to analyze machine-generated data, identify patterns, and optimize production processes [32].

- **Visual Computing:** Advanced visualization tools in IMES improve human-machine interfaces
enabling intuitive data display and analysis [15].

- **Blockchain Technology:** While not directly tied to IMES, blockchain can enhance supply chain transparency and secure production data, indirectly supporting IMES operations [17].

4. Case studies presenting the deployment of IMES in food and beverage companies

The implementation of IMES in the food and beverage industry represents a significant step toward the digitalization of industrial processes. This section presents eight real case studies that illustrate the implementation of IMES, discussing various technologies used, benefits achieved, challenges encountered, and key success factors in a highly regulated and quality-guided environment.

4.1. Specific requirements of the food and beverage industry

Before examining the case studies, it is essential to understand the fundamental requirements of this sector, characterized by strict regulations, high competitiveness, and growing demand. It also faces low profit margins, making the implementation of IMES difficult and complex.
In this sector, the final consumer is human; traceability, hygiene, and food safety [35] are essential pillars of production. This field also presents technical and organizational specificities that demand high standards in production [7]:

- Raw materials and semi-finished products often possess dynamic characteristics that evolve over time. Raw milk serves as a perfect example of this. If it is not pasteurized or cooled quickly after milking, it begins to deteriorate within a few hours. This sensitivity necessitates strict processing timelines and rigorous storage conditions to maintain product quality and prevent any loss.

- The recycling of products or semi-finished goods is a common practice in many processes. In the chocolate industry, recycling molding scraps is standard. Production surpluses or broken pieces, such as chocolate bars or candies, are remelted and reintegrated into a new production cycle. This practice helps minimize material losses while maintaining the quality and taste properties of the final product.

- The safety and quality of finished products depend on multiple factors, including the hygiene of the environment, equipment, personnel, transportation, and storage conditions. In a beverage production plant, ensuring the safety and quality of finished products is essential. Environmental hygiene is maintained through sterile white production zones, where air is filtered and controlled to prevent contamination. Equipment such as mixing tanks and production lines is cleaned automatically using CIP (Cleaning In Place) procedures to ensure no residue remains between production cycles. Personnel must follow strict protocols, including wearing hairnets, shoe covers, and gloves, and undergoing regular health checks.

- Raw materials, semi-finished products, and finished products are generally perishable and have a limited shelf life. For example, soft cheese is a semi-finished product that requires maturation. However, it can deteriorate quickly if storage conditions are not properly maintained, particularly in the case of insufficient refrigeration.

To comply with regulations regarding safety and traceability, manufacturers must implement safety principles in their production processes such as [7]:

- Good Hygiene Practices (GHP)
- Good Manufacturing Practices (GMP)
- Hazard Analysis and Critical Control Points (HACCP) system, aimed at analyzing hazards and controlling critical points.

4.2. Case studies of IMES in the food and beverage industry

To illustrate the implementation challenges and success factors of IMES in the food and beverage industry, this section presents a selection of case studies collected from various manufacturers, including dairy, meat, dietary supplements, brewing, and beverages.
These case studies were chosen for their relevance to Industry 4.0 integration, their documented outcomes, and their representativeness of the industry's digital transformation journey. Among these, particular attention is given to a local case study conducted at EC-CBC, which provides a detailed and contextualized example of IMES deployment in a real-world production environment.

Case study 1: Dairy manufacturing company - Scandinavia

The author of [36] discusses a case concerning a leading dairy manufacturing company specializing in the production of organic dairy products, with facilities spread across Scandinavia. To meet increasing consumer demands for transparency regarding product origins and operations, including animal treatment and farm hygiene, the company required enhanced data collection capabilities and information transparency across its supply chain. Additionally, it aimed to improve logistics, food quality, flexibility, scalability, and establish a strong foundation for data management and digital services.
In 2018, the company commissioned an IoT platform for its food supply chain, integrating real-time data acquisition and process monitoring into its MES to enhance its capabilities. To ensure optimal interoperability between IT and OT (Operational Technology) systems, the platform adhered to open standards including ISA 95 and RAMI 4.0.
Using MQTT and OPC UA protocols, the company connected all 23 of its factories to the IIoT, enabling both centralized control and decentralized decision-making. The IMES served as a process digital twin by offering real-time insights into production processes, which helped identify issues that were previously misdefined through manual data collection.
The company collaborated closely with its suppliers and IT architects during the implementation phases to adapt the IMES to meet specific operational requirements, such as integrating existing equipment and coordinating with suppliers. With enhanced shop floor planning software, the company was able to reduce changeover times and increase delivery speeds despite challenges like supplier limitations and siloed solutions. Full traceability is achieved through the implementation of RFID tags and wireless sensors added to the material and component levels.
Although it's still challenging to quantify productivity gains, the company estimates a significant improvement in operational efficiency, particularly in reducing stock levels through advanced predictions and enhancing resource utilization. The company is completely satisfied with the IMES, which supports essential features like real-time scheduling, predictive maintenance, and operator support for tasks such as color and mold changes.

Case study 2: European Pork and beef producer

In [36], there is a second case concerning a major international meat processing business that operates across Europe and specializes in the production of beef and pork. The company required enhanced planning, resource management, and process transparency within its complex supply chain environment to meet the stringent requirements for food safety, traceability, and operational efficiency.
In 2018, the company installed a new high-technology MES/MOM (Manufacturing Operations Management) platform to reduce data silos and improve communication between IT and OT systems. The proper use of the ISA 95 standard and the adoption of respective transport and semantic protocols such as MQTT and

OPC UA were further deemed essential for successful Industrial IoT integration. By supporting open industry standards, the company aimed to improve connections between its central IT department, farms, and factory networks while maintaining legal compliance.
The IMES provided reliable batch, quantity, and stage monitoring, ensuring complete product traceability from farm to fork. Maintaining this feature was important for monitoring parameters that affect meat quality, such as processing time, temperature control, and machine sanitation. With increased visibility came improved operational reliability, resource management, and production scheduling, notably decreasing raw material inventories and storage costs. As a result, the system paved the way for advancements in logistics, allowing real-time information sharing to better communicate fresh food supply chains.
Throughout the implementation, senior IT architects and global IT leaders collaborated closely with factory operators and supply chain managers to design the IMES solution that addresses specific process needs and operational constraints. The complexity of integrating past systems makes it challenging to quantify productivity gains, but the company estimates a significant increase in overall efficiency. There is complete satisfaction with the IMES, particularly regarding its ability to support essential functions like the workshop for packaging finished products and the production of required certificates of analysis for the food industry.

Case study 3: DSM Nutritional Products - France

This case [37] concerns DSM Nutritional Products, a leading company specializing in the production of vitamin and carotenoid premixes, with a facility in Village Neuf (Haut Rhin, France). To meet stringent production deadlines, which allow no more than four weeks between order receipt and finished product shipment, including the issuance of analysis certificates, DSM required enhanced process transparency, planning, and traceability capabilities in a demanding food industry environment.
In 2013, ABB deployed a comprehensive IMES that integrates real-time operational management. This system comprises seven extended 800xA control command stations and the cpmPlus ECS (Enterprise Control System), a middleware solution linking IMES with the ERP system via ISA 95 standard interfaces, with 15 dedicated stations all running on virtualized servers to ensure robustness and flexibility. The IMES provides precise tracking of produced batches, quantities, and stages, ensuring complete product traceability in compliance with regulatory requirements. This increased visibility enhances operational reliability, resource management, and production scheduling, resulting in a notable reduction in raw material inventory and optimized storage costs.
As part of the performance engagement process, ABB engineers worked closely with the DSM premix team to adapt the IMES to specific process needs and operational constraints. While it is challenging to quantify productivity benefits, DSM estimates an overall productivity increase in double figures. As a company, DSM welcomes the IMES solution in support of essential operations, including the finished product packaging workshop and, in the food industry, certificates of analysis generation.

Case study 4: Wander AG - Switzerland

In [37], a second case discusses Wander AG, a renowned producer of Ovaltine and Caotina chocolate malt drinks with a facility in Neuenegg, Switzerland. To address the growing demands for capacity and flexibility in a production environment that had evolved over several decades, Wander sought to modernize and rationalize its processes.
In 2016, ABB implemented a comprehensive IMES solution for real-time operations management, which included cpmPlus ECS and bidirectional integration with ERP systems and numerous control stations across the facility. The IMES maintains perfect horizontal and vertical integration from raw material delivery to finished product dispatch, ensuring full traceability of materials, equipment, and personnel.
The IMES enables precise tracking of production orders, materials, and stages to ensure full traceability of products and compliance with regulatory requirements. With greater awareness, it is directly linked to operational reliability, resource management, and production scheduling, which has significantly reduced raw material inventories and optimized storage costs.
During implementation, ABB engineers collaborated with the production team at Wander to customize the IMES to specific process needs and address any other constraints that may hinder its operation.
When it comes to quantifying gains, Wander accounts for significant improvements in efficiency, flexibility, and productivity. The company is entirely satisfied with the IMES that supports essential operations such as raw material handling, batch formulation, and packaging. The IMES also produces requisite certificates of analysis while ensuring compliance with hygiene and service delivery standards.

Case study 5: Beer manufacturing company - Germany

Authors of [9] describe the case of a traditional brewery, Weihenstephan, that employs model-driven engineering (MDE) to develop a MES in the brewing process. Preparing the beer involves a series of operations termed mashing, lautering, boiling, and cooling, which require accurate and highly transparent control to fulfill quality and regulatory requirements. Due to the high customization effort typically associated with such implementations, the company chooses MDE to simplify deployment, facilitate changes to energy monitoring, and enhance operational efficiency.
The IMES solution has been developed using predefined modeling elements and organized into four libraries: plant, process, IMES function, and report. The brewery first constructed the technical systems (such as mash tun and lauter tun) along with the associated data points based on the established energy consumption, using ISA 95 and Weihenstephan Standards to ensure accurate communication and data exchange. Brewing processes were divided into stages (mashing,

boiling) and operations (heating, stirring) to enhance MES functions for calculating KPIs and energy usage. By mapping these models, the company was able to dynamically generate an IMES prototype tailored to its operations.

Throughout the implementation, the brewery adjusted its process to facilitate real-time monitoring and control of energy consumption and equipment efficiency. Despite the lack of a fully operational IMES generator, the modeling phase was validated through expert feedback, demonstrating improved communication, reusability of elements, and readiness for future automation. RFID systems and standardized modeling tools were utilized for an audit of existing physical processes to enhance traceability and data accuracy across the brew house.

Although not fully automated yet, the brewery has made improvements in process modeling clarity, the potential for future IMES integration, and reduced manual configuration needs. This case demonstrates the suitability of a model-driven IMES approach for SMEs in the food and beverage sector looking to digitize their operations efficiently and flexibly.

Case study 6: Dairy manufacturing industry - Malaysia

The authors of [38] regarding the usage of MES within the Malaysian dairy context minimized it to the Halal food environment. The nation hopes to position Malaysia as a global halal hub and is therefore encouraging dairy manufacturers to adopt digital solutions to improve traceability, production efficiency, and quality management. The industry faces numerous internal challenges, including minimal production data, weak integration between management and operations, as well as increased regulatory demands.

The introduction of IMES has been recognized as a key technology for transparency, traceability, and real-time monitoring. It is important to note that most of these modules have been implemented in Malaysia's dairy processing systems, even though IMES was still in the early stages of implementation. They have deployed modules for data acquisition, quality control, electronic batch records, and inventory management.

Additionally, IMES has been made available for ERP and WMS integration, thereby providing better coordination of production and logistics functions.

The IMES implementation strategy focuses on optimizing material handling and minimizing human error, and includes features such as barcoding, RFID-based traceability, automated weighing systems, and electronic Kanban boards.

Furthermore, IMES supports real-time device monitoring, predictive maintenance, and fault-proof feeding to achieve operational enhancement and reduce production costs.

The initial IMES applications have faced challenges, including the high cost of investments and staff training. Yet, they have successfully recorded improved accuracy in the data, reduced material wastage, enhanced halal compliance, and increased production transparency. The study indicates that the complete adoption of IMES would position the Malaysian dairy industry to enhance its competitive edge and sustainability by ensuring compliance with international standards and consumer expectations.

Case study 7: Cultivated meat manufacturing industry - Global perspective

In [39], the case study illustrates a sector that is rapidly developing to address global issues of food sustainability, environmental impact, and health. The term CM designates the in vitro cultivation of animal cells capable of generating meat products with a taste and nutritional profile similar to traditional meat offerings while addressing ethical and environmental concerns. For the large-scale, efficient, and safe production of meat products, it requires advanced digital tracking capabilities with real-time monitoring, intelligent automation, and data-driven decision-making throughout the entire value chain. In this case, several CM companies, such as Eat Just, Mosa Meats, and Orbillion, have begun implementing adapted Industry 4.0 environments and are showing their interest in converting their current systems into AI, ML, IoT, and blockchain technologies in both upstream and downstream operations. Programs such as AI-based cell screening, real-time bioreactor monitoring using IoT sensors, innovative packaging, predictive maintenance, and blockchain-enabled traceability have been developed. IMES solutions, along with ERP tools, were deployed to link production data to business processes. Such digital solutions are designed to offer flexibility, efficiency, and transparency while scaling CM production systems.

The implementation faced challenges such as high infrastructure costs, integration with legacy systems, workforce upskilling, and, of course, the adoption of cybersecurity requirements. Nonetheless, industries laid the groundwork for intelligent CM factories by deploying a phased digital adoption strategy, beginning with cloud data storage and culminating in IIoT and digital twins. Other technologies, including AR/VR, were utilized for operator training and customer interaction, while RFID systems were introduced for real-time traceability throughout the supply chain. Options for quantifying cost or yield improvements are limited due to the industry's early stage. However, companies do report increased operational control and enhanced product consistency, as well as adaptability to the market. Stakeholders cite improved forecasting and resource optimization, along with the ability to customize a product's design according to consumer preferences, as the main beneficiaries of ongoing digitalization in the cultivated meat sector. They express optimism regarding the long-term impact of Industry 4.0 on cultivated meat businesses.

Case study 8: Beverage manufacturing industry - Algeria (ECCBC)

Equatorial Coca Cola Bottling Company, or ECCBC, in Algeria has adopted a well-structured action plan and a strict operational ethic in pursuit of its ambitious goals. To align organizational efforts toward excellence, ECCBC has established a strategic framework built around five central pillars. The first pillar concerns safety, quality, and operational sustainability; the second focuses on service levels, production capacity, and capability; the third centers on operations and cost efficiency; the fourth aims to optimize cash capital. Finally, the fifth pillar emphasizes operational excellence in standardization, reinforcing consistency and overall process performance. To support this strategic structure, ECCBC has two important enablers: the staff development program, which encourages employee commitment, self-sufficiency, and expertise; and the technology and digitalization program, which upgrades processes and accelerates digital transformation. These two levers serve as enablers, creating a foundation for real and impactful initiatives. This global framework serves as a comprehensive reference guide for all ECCBC operational teams. It steers all projects and programs toward achieving the company's vision. In this context, monitoring and enhancing OEE is central to the system, facilitating effective interaction between the pillars and catalysts. Consequently, ECCBC needed to identify a solution that would yield precise OEE measurements across all factories while also meeting specific factory requirements and operational specifications. Initially, the plant recorded data manually using Excel, which presented many limitations. The downtime documented by line managers was not consistently recorded, speed losses were not identified, and the absence of a real-time dashboard hindered immediate data entry and responses to production incidents, causing significant delays. Furthermore, the lack of remote monitoring and the questionable reliability of the collected data severely restricted analysis and decision-making capacity. Based on this analysis, a decision was made to implement an IMES with the appropriate technologies and strategies for process digitalization. Such a system automated data collection, centralized production information, and provided real-time visibility into performance. The analysis of old production reports identified major gaps in performance monitoring and control. First, there was no structured shift-based tracking system, making it difficult to assess performance on a team basis or track the timing of production events. Additionally, key indicators like OEE, which combines performance, availability, and quality, were neither computed nor utilized, stifling unbiased assessments of overall machine effectiveness. The report also lacked precise data on the quantity produced per shift or hour, hindering detailed analysis of performance variations throughout the day. Regarding production downtime, no distinction was made between operational downtime, equipment downtime, or planned stoppages, and no type of downtime was specifically categorized, which hindered any strategy to reduce idle time. Furthermore, data related to the EPRS (raw material tracking) was insufficient, particularly concerning consumed material quantities, recorded losses, and the management of components like syrup or performs. This overall lack of visibility and data reliability was a major barrier to performance optimization and underscored the need for an IMES that would enable precise, real-time, and automated tracking of production operations. After analyzing operational needs, it is essential to gather the expectations of the various users involved in the production process. Operators, on the front lines, expressed the need for a simple, intuitive, and easy-to-use interface that would allow them to enter or consult data without complexity or time loss. On their side, production, maintenance, and quality managers emphasized more strategic issues, including reducing the administrative burden associated with manual reporting, improving the reliability of collected data, and ensuring complete traceability of production events. They also expect real-time visibility of line performance to facilitate decision-making and optimize interventions. Based on these expectations, the objectives of the IMES project were clearly defined: improve OEE by acting on availability, performance, and quality, ensure the reliability and automation of data collection, and offer real-time supervision of operations, thus laying the foundations for proactive, data-driven production management. After analyzing needs and gathering user expectations, it was necessary to define the functional and technical specifications of the system to be implemented. The first steps were to determine the key features required concerning the previously defined objectives: automated data collection and credibility, real-time visualization, report generation, traceability, downtime tracking, and yield monitoring. Following this, the selection of the equipment to connect was precise. For example, introducing IoT sensors would allow for IMES system installation, enabling automatic and continuous reporting of production data from the lines (Figure 4).

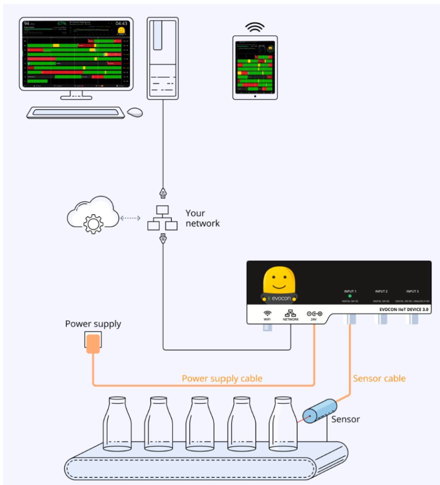

Figure 4: Integration of IIoT Devices for Automated Production Line Monitoring[40]

Meanwhile, a technical constraints evaluation was conducted, considering the existing network infrastructure, information technology security requirements, and compatibility with the current systems, particularly the SAP ERP system, to ensure coherent integration within the company's overall digital environment (Figure 5).

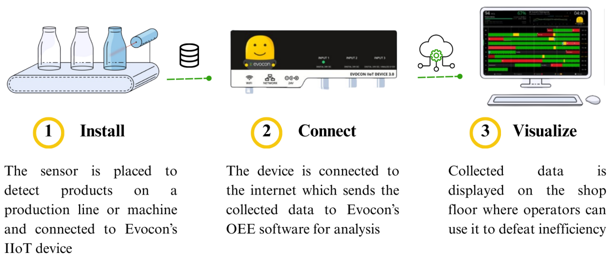

Figure 5: Installation Steps of IIoT System [40]

The implementation of the IMES Evocon solution was customized according to the company's needs and integrates various functions, including the following:

OEE Tracking: The system allows real-time OEE tracking, but at this stage, does not factor in quality in the calculations (Figure 6).

Figure 6: OEE tracking in Evocon

Equipment Downtime Tracking: Evocon automatically detects and records machine downtime, making it easier to identify the causes of production loss and implement corrective actions (Figure 7).

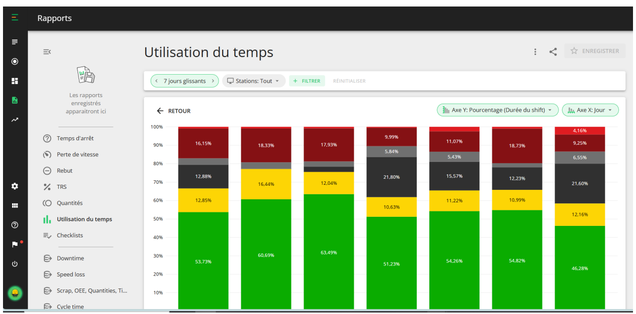

Figure 7: Equipment Downtime Tracking in Evocon

Speed Loss Tracking: The system analyzes the difference between theoretical and actual equipment speeds, enabling the detection of performance losses that are often unnoticed (Figure 8).

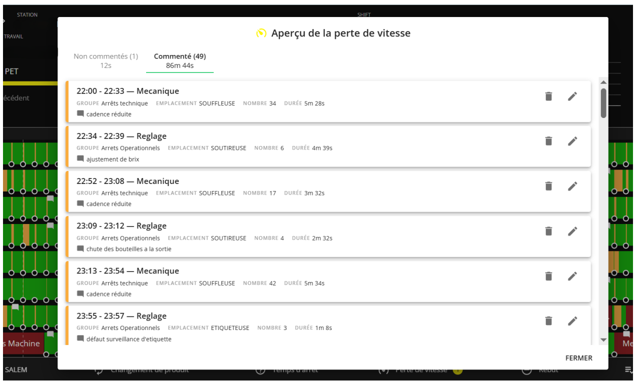

Figure 8: Speed Loss Tracking in Evocon

Personnel Performance by Shift Tracking: Evocon enables the assessment of operators' collective performance by shift, enhancing visibility on human efficiency and fostering effective team management.
Quality Control Tracking: The system integrates the tracking of specific quality control parameters, such as product coding, which enhances compliance and batch traceability.
Reporting and Analysis: The solution offers an automated reporting and analysis mechanism that enables quick and informed decision-making at all levels of the organization (Figure 9).

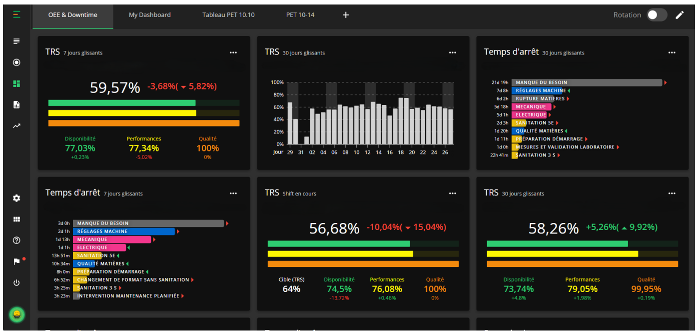

Figure 9: Reporting and Analysis in Evocon

Beyond these customized features, the integration of IMES Evocon began in 2024. It was deployed at the start of 2025 and has continued to the present day, bringing significant operational advantages at various levels of the company. One essential benefit is the improvement in data reliability. Errors caused by human intervention in data collection are almost eliminated, allowing for maximum accuracy, consistency, and validity of information.
This has led to greater reliability and notably reduced the time required to analyze and track performance due to centralized data repositories and integrated analytical tools that quickly identify issues and ensure performance verification.
Furthermore, the system fosters better intergroup communication, as real-time data sharing between different subsidiaries enables smoother coordination and enhanced responsiveness. Data security is also a key asset of IMES, which offers reliable solutions for backup,

access management, and protection against data loss or tampering. Automating data collection minimizes human errors, resulting in reliable, consistent, and actionable information. With this reliability, shortened analysis and tracking time arise from the integration of centralized data with advanced analysis tools, facilitating quick issue detection and performance reviews. Intergroup communication improves since real-time data sharing among various subsidiaries leads to better coordination and faster response times.

Data protection is an essential advantage of IMES, which also provides solutions for backup and access management against destruction and/or modifications. Evocon believes that production data must be secure and confidential. Data is the sole property of the client, hosted in Europe on the Amazon AWS environment, and secured with strong encryption (AES-256-GCM). Access is strictly controlled, connections are secure, and backups are automated and replicated. Evocon, certified ISO/IEC 27001: 2013, ensures compliance with international standards for information security, risk management, and business continuity.

The application, therefore, notably enhances reporting by enabling automatic generation of detailed, customizable reports, thereby assisting with strategic and operational management. Tracking data in real-time allows for close monitoring of production and provides immediate intervention when issues arise. In terms of productivity, this system offers better visibility on performance and losses, enabling quick identification of optimization levers and process improvements. Data is deleted, in the event of termination, by following the strict procedures established for this purpose. IMES promotes the monitoring of personnel by displaying operators' activities and positions, along with their performance, thus enhancing human resource management. It also strengthens traceability, as all production steps are automatically recorded, making audits practical and ensuring total transparency. Lastly, structured and secure data archiving creates a solid historical record, which is necessary for time trend analyses, benefits tracking, and maintaining continuous improvement efforts.

However, despite the numerous advantages provided by IMES Evocon, some limitations were observed during its deployment and usage on the ground.

One of the main constraints lies in the fact that downtimes are recorded by line without specifying the exact equipment involved, which limits analysis and makes it difficult to identify the causes of malfunctions quickly. Additionally, the quality of comments input into the system is often quite inadequate, especially when it relates to the skill levels of operators, affecting the relevance of the information collected. Technically, using Wi-Fi as the connectivity mode results in instability, as loss of connection and data may occur at any time, rendering the system unreliable.

Furthermore, problems related to sensor degradation, such as reading errors due to sensor wear or the presence of beverages in sensors, skew the readings. Raw material consumption is still monitored manually; thus, no automation exists, which increases the risk of errors. Humidity conditions on production lines also affect touch screen functionality, making the IMES interface less smooth to operate. In light of these limitations, technical and organizational adaptations need to be made for the optimal integration of the Evocon system.

5. Discussion

IMES integration involves new trends, lessons learned, and ongoing challenges in the food and beverage sector. By analyzing the eight case studies (see Table 2), standard technologies, success factors, and barriers were identified, providing this documentation with a comprehensive and thorough discussion of the deployment of IMES in this sector.

To provide a structured analysis of the case studies, a systematic approach is adopted, and the flow of ideas is organized into two distinct phases: before implementation (5.1) and during and after the implementation of the IMES (5.2).

- Before the implementation, attention is focused on defining needs and describing expectations, similar to a preliminary study that clarifies objectives, functionalities, and the technologies considered.
- The implementation encompasses the aspects encountered both during and after its execution, including obstacles faced, technology integration, and the results achieved.

Furthermore, the comparative analysis of the cases has highlighted the challenges and specific functionalities identified as critical success factors (5.3).

5.1. Before the implementation of the IMES

As practice states, the essential initial requirement in a systematic approach is to identify what the requirements and expectations involve, serving as a foundational analysis that clarifies goals, features, and other potential technologies.

Companies typically initiate IMES projects focusing on specific needs such as improved data collection, achieving real-time monitoring, resource management, traceability, and intelligent production planning. For example, the Scandinavian dairy manufacturing company sought better transparency and real-time insights from IoT digital twins, while the European pork and beef producer required end-to-end traceability to meet stringent food safety standards. Other companies, such as DSM Nutritional Products and Wander AG, aimed for more reliable and flexible operations in conjunction with ERP system integration and real-time process visualization.

These cases reveal that industry-specific pressures, such as compliance with food safety regulations, process variability, and high demand for traceability, play a central role in shaping IMES requirements. Objectives frequently revolve around operational efficiency, integrating lean manufacturing and operational excellence strategies, as well as sustainability, quality assurance, and digital transformation in line with the Industry 4.0 paradigm.

Technologies such as IoT, AI, ML, and BDA were selected to meet functional expectations, including real-time monitoring, predictive maintenance, traceability, quality control, and inventory optimization. Furthermore, technical specifications considered factors like system interoperability with standards such as ISA 95, SAP ERP compatibility, cybersecurity, and the need for intuitive operator interfaces.

5.2. During and after implementation of the IMES

The second phase explores the actual developments during and after IMES implementation, focusing on technology integration, encountered obstacles, and achieved results. Across the cases, technology integration demonstrated widespread adoption of advanced tools.

Core technologies such as IoT and AI-enabled capabilities like predictive maintenance and smart packaging, particularly in cultivated meat manufacturing.

Complementary technologies, including blockchain for traceability and augmented reality/virtual reality for operator support, were also utilized.

However, a high level of challenges accompanied IMES deployment across the analyzed case studies. Integration complexity was pervasive when connecting new IMES with heterogeneous legacy systems, as evidenced in the European pork and beef case. The origin refers to the wide variety of software platforms used in production environments, which include ERP, LIMS (Laboratory Information Management Systems), and PPS (Production Planning Systems) that ensure a smooth flow of information, thus presenting a significant technical hurdle.

In addition, there is complexity in adjusting IMES characteristics to the specific features of food and beverage manufacturing operations. Such processes can be batch, continuous, or discrete, and they are often combined in convergent or divergent forms.

Systems must manage yield variability, frequent recycling, recipe differences, and strict hygiene and safety requirements, particularly at Weihenstephan Brewery. Additionally, high investment costs emerged as one of the primary barriers, particularly for SMEs, such as those in the dairy sector in Malaysia. In this context, the need for standardized modular IMES solutions becomes crucial; otherwise, the complexity of customization and implementation costs can become challenging to manage. Regarding standardization, the initiation of platforms like the Weihenstephan Standards aims to provide a universal communication protocol and maintain data consistency across systems.

Resistance to organizational change and the need for workforce upskilling were additional critical issues, particularly in an early-stage industry like cultivated meat. Technical fields included all: Wi-Fi instability, sensor degradation, and poor-quality data input were typical operational challenges, as observed with EC-CBC's installation, for example.

These limitations were further compounded by environmental conditions; numerous examples exist, such as humidity affecting touchscreen functionality, cybersecurity concerns, and the absence of real-time dashboards, which impaired visibility and slowed responsiveness.

Moreover, IMES must be capable of collecting and managing detailed traceability and food safety data, covering raw material origins, production processes, and hygiene conditions. Ensuring compliance with strict standards such as GHP, GMP, and HACCP is critical; it enables the system to offer planning, execution, and monitoring functionalities that are reliable. Flexibility is yet another challenging requirement; IMES must adapt quickly to any changes in consumer demand or new product variations, particularly in highly competitive markets.

Finally, sustainability efforts should be supported by IMES integrating and analyzing energy consumption data for KPI calculations[41], such as OEE, and identifying opportunities to improve production efficiency while decreasing environmental impact.

Despite these barriers, the eight cases demonstrated reasonably good operational gains. Improvements include enhanced real-time visibility, operational efficiency, product traceability, stock level reductions, and minimized material losses throughout the chain.

For instance, Evocon IMES implemented by ECCBC Algeria provided a new edge towards improved monitoring and traceability of OEE. Improvements in productivity, flexibility, and stock optimization for DSM Nutritional Products and Wander AG were particularly pronounced, while operational transparency and energy management were further advanced using a model-driven approach at Weihenstephan Brewery, with total automation still on the horizon [42].

Table 2: Summary of Case Studies - Source: Author's work

Case Study and Reference	Objectives	Requirements	Year	Technologies Used	Main Features	Challenges	Results
Dairy manufacturing company - Scandinavia [36]	Improve operational efficiency, traceability	IoT platform, interoperability, real-time monitoring	2018	IoT, ISA-95, RAMI 4.0, MQTT, OPC UA, Digital Twin	Real-time insights, predictive maintenance	Complex system integration, difficult productivity quantification	Improved stock management, resource utilization
European Pork and Beef Producer [36]	Enhance safety, traceability, resource management	End-to-end tracking, IT and OT system integration	2018	IMES, IoT, MQTT, OPC UA	Full batch tracking, real-time monitoring	Integration with legacy systems	Notable operational efficiency improvement
ABB - DSM Nutritional Products [37]	Real-time operational management, traceability	Integration with ERP, virtual servers	2013	IMES, 800xA, cpmPlus ECS	Batch tracking, stage management	Complex productivity assessment	Increased productivity, cost reduction
ABB - Wander AG [37]	Modernize production, flexibility	ERP connectivity, real-time visualization	2016	IMES, cpmPlus ECS	Batch formulation, material handling, compliance monitoring	Difficult gain quantification	Improved efficiency, flexibility, productivity
Weihens-tephan Brewery [9]	Energy efficiency, operational transparency	Mode-driven IMES, energy monitoring	2018	RFID, ISA 95, MDE approach	Dynamic IMES generation, process transparency	No fully operational IMES generator yet	Enhanced process modeling clarity
Malaysian Dairy Industry [38]	Traceability, Halal compliance	ERP/WMS integration, real-time tracking	2021	RFID, barcodes, predictive maintenance modules	Inventory management, quality control	High investment, early stage adoption	Improved data accuracy, waste reduction
Cultivated Meat Industry [39]	Flexibility, transparency, scalability	Industry 4.0 platforms, smart systems	2024	IoT, AI, ML, CC, VR, DT, RFID, Blockchain, ERP	Bioreactor monitoring, traceability, predictive maintenance, smart packaging	Infrastructure cost, workforce upskilling	Improved operational control and product consistency
ECCBC Algeria	Standardize production performance monitoring	IoT sensors, SAP ERP integration	2024 /2025	IMES Evocon, IIoT sensors	OEE tracking, downtime recording, real-time visualization	Wi-Fi instability, sensor degradation, manual raw material tracking	Improved performance visibility, traceability, data security

5.3. Challenges and Success Factors

The implementation cases at ECCBC, a Scandinavian dairy company, and cultivated meat manufacturers greatly emphasized real-time monitoring. Quality control, primarily enhanced by AI-based vision systems, has become an essential topic in the Malaysian dairy industry. Complete traceability, a key requirement for compliance and food safety, was evident in the implementations of ABB and the cultivated meat sector, where blockchain technology provided transparency. Inventory management has been significantly improved at the sites of ABB and ECCBC, and predictive maintenance is being implemented, particularly in the dairy and cultivated meat projects. OEE calculation, a fundamental performance indicator, has been systematically deployed using specialized solutions like Evocon. Certain key elements for success were consistently highlighted in the various case studies. Collaboration across functions, including IT, production, and supply chain teams, was identified as critical for successful integration. Establishing key performance indicators and specific requirements before the start of the implementation project ensured that technology and business needs were well aligned. Seamless integration with existing systems, such as ERP or LIMS, facilitated easier transitions, while the careful selection of an intuitive and modular IMES platform promoted user acceptance and minimized resistance. Managing data quality through automated data collection greatly improved the process of making informed decisions. Training personnel and developing proactive change management plans were essential for system acceptance and sustainability across all cases studied. Furthermore, in the cases analyzed, standardization approaches such as ISA 95 and Weihenstephan standards helped ensure interoperability and scalability. Nevertheless, these challenges remain to be overcome. A considerable level of technical expertise is required to coordinate IMES with complex legacy environments. Substantial initial investments, particularly for SMEs, often make phased deployment the only option. The cultural barrier to technological change, combined with issues of technical robustness like sensor drift and Wi-Fi reliability, continues to affect system performance adversely. Environmental conditions such as humidity lead to touchscreen failures in beverage manufacturing; furthermore, increased digital connectivity brings added complexity by posing cybersecurity threats. Modifying the IMES to support various production types— specifically batch, continuous, and discrete—presents a challenge in ensuring traceability and food safety compliance, which remains a significant hurdle, particularly in highly regulated industries. The cross-case insights highlight common factors that contribute to success, as well as challenges prevalent across the set, all of which uniquely shape various IMES implementations. To summarize these findings, the following figure 10 integrates several success factors throughout the IMES implementation life cycle, from preparation to deployment to stabilization. This figure also represents challenges organized into different perspectives: technical, organizational, and environmental aspects that have influenced the success of IMES.

6. Conclusion

This study aimed to explore how MES evolves within the framework of Industry 4.0, particularly in the food and beverage sector, by integrating AI, IoT, and Big Data Analytics to enhance automation, reconfigurability, and real-time decision-making in smart factories.

The study demonstrates that Intelligent Manufacturing Execution Systems (IMES) effectively tackle industry challenges in the food and beverage sector, such as market shifts, regulations, and sustainability goals. IMES plays a crucial role in enabling innovative, sustainable, and flexible manufacturing environments. It aligns with Industry 4.0 aims, enhancing flexibility, responsiveness, and sustainability. IMES implementation leads to operational benefits such as automated monitoring, reduced waste, and improved responsiveness to consumer needs. Additionally, IMES improves data management and analysis, enhancing real-time tracking and responsiveness. It also facilitates process improvements, enhances traceability and compliance, optimizes resource and inventory management, and enables predictive maintenance. The study concludes that IMES can promote continuous improvement and strategic decision-making by transforming massive production data into actionable insights through advanced analysis tools.

The study focuses on integrating emerging technologies into manufacturing operations systems (MES) within the food and beverage industries. It outlines the study's limitations, including its reliance on qualitative case studies, emphasis on theoretical models, neglect of small and medium-sized enterprises (SMEs), and the use of simulation-based case studies. Additionally, it highlights challenges such as high investment costs, integration complexity, issues with technical robustness, manual processes, and concerns regarding data quality and specificity. The study also addresses organizational challenges like resistance to change, the need for workforce upskilling, and cybersecurity issues related to increased digital connectivity. Future research should incorporate quantitative analyses to measure the long-term impact of IMES on operational performance and sustainability. It should also explore how IMES can be modified to support operational excellence, automation, and smart supply chains. Additionally, industry-specific adaptations and standardized modular solutions for SMEs are necessary. Enhancements in data quality and specificity are needed, and technical limitations must be addressed. Predictive maintenance should be integrated into IMES models for Industry 4.0, and integration with technologies like Digital Twins could assist in simulating realistic scenarios and optimizing processes.

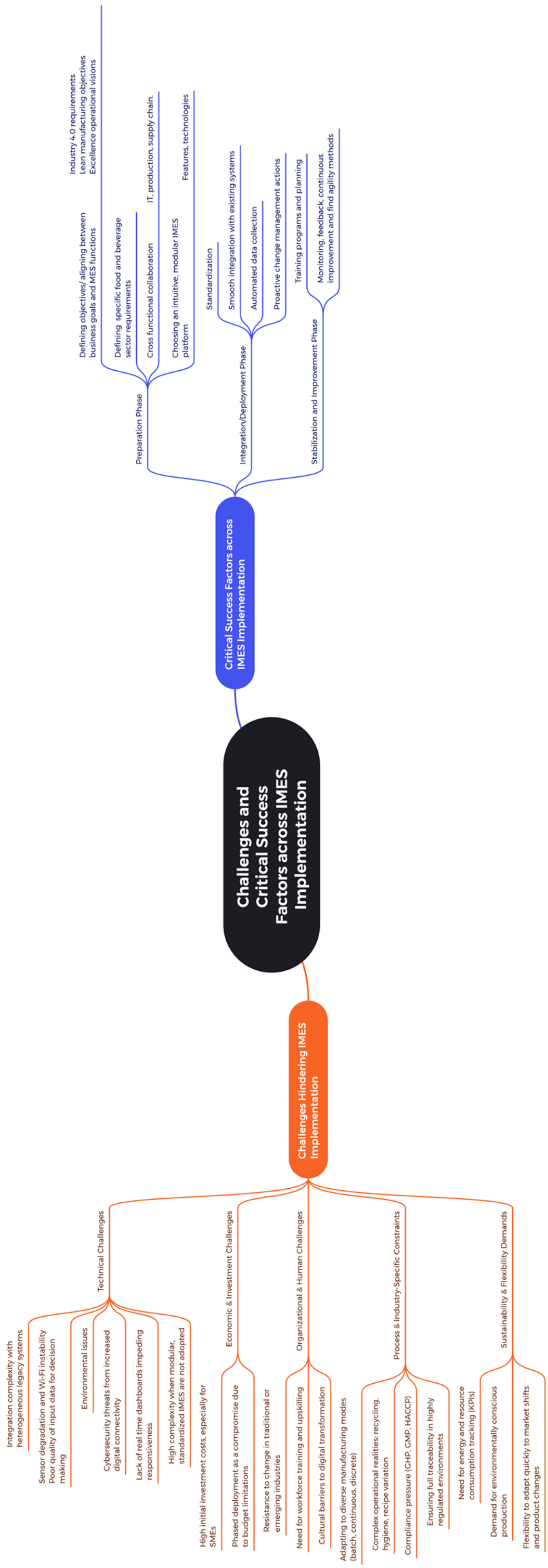

Figure 10: Critical Success Factors and Challenges across IMES Implementation - Source: Author's work

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