applied sciences

MDPI

Article

Integration of Fog Computing in a Distributed Manufacturing Execution System Under the RAMI 4.0 Framework

William Oñate [1,2,*] and Ricardo Sanz [1]

[1] Departamento de Automática, Universidad Politécnica de Madrid (UPM), 28006 Madrid, Spain
[2] Departamento de Electrónica, Universidad Politécnica Salesiana (UPS), Quito 170146, Ecuador
* Correspondence: wonate@ups.edu.ec

Abstract: Technological progress has driven the integration of new technologies in the field of industrial automation, but a structured framework is often lacking to efficiently guide the transition from traditional industries. This article presents the implementation of advanced technologies on FESTO's (MPS-500) modular production system, using the reference architectural model for Industry 4.0 (RAMI 4.0) as a guide for scaling. It highlights the importance of the synergy between information technologies (ITs), which enables the development of a multi-level processing system. This system performs concurrent tasks, thus managing execution and manufacturing through an MES based on requests from the cloud. On the other hand, at a lower level, a fog computing system was integrated, which relieves the processing load by distributing processes locally. In addition, matrix mapping was performed to map the integrated technologies within the context of a reference model, allowing a clear alignment between the different levels of the system. The results show a significant reduction in waiting times between batches and operations, which directly improves productivity and offers greater flexibility, that is crucial for SMEs during their growth and scaling process towards Industry 4.0.

Keywords: MES; fog computing; RAMI 4.0; IoT; Industry 4.0

Citation: Oñate, W.; Sanz, R. Integration of Fog Computing in a Distributed Manufacturing Execution System Under the RAMI 4.0 Framework. *Appl. Sci.* **2024**, *14*, 10539. https://doi.org/10.3390/app142210539

Received: 11 October 2024
Revised: 10 November 2024
Accepted: 12 November 2024
Published: 15 November 2024

1. Introduction

Several systematic literature reviews (SLRs) have been mentioning, for several years now, the importance of the evolution of technological innovation in the manufacturing production sector in optimizing production processes, improving operational efficiency and significantly reducing costs, thus strengthening the competitiveness of companies by enabling them to respond quickly and effectively to market fluctuations [1–3]. To that end, some academic papers show implementations of transforming and/or designing factories into highly connected smart ecosystems [4]. This is already known to be possible thanks to the advanced integration of different operational technology (OT) and information technology (IT) pillars that constitute and are part of Industry 4.0 for automation [5,6].

1.1. Opportunities in Industry 4.0 Compared to Industry 3.0

The characteristics of the third industrial revolution have allowed for improved efficiency and precision in manufacturing production [7]. Despite this, they have disadvantages compared to the new Industry 4.0 era in terms of the lack of interconnectivity, the limited ability to customize products in batches, the reliance on sub-processes within the production chain to adapt quickly to real-time changes and even the technological skills that factory maintenance operators must possess [8]. Consequently, for corporations, SMEs and MSMEs to be more productive and competitive nationally and globally, it is essential to scale up to Industry 4.0, integrating advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), computer vision (CV), distributed computing systems (cloud, fog and edge), wireless connectivity and big data [9–12].

Despite the advantages of I4.0 over I3.0, there are case studies that add functionalities to Industry 4.0 which are supported by traditional architecture standards such as ISA-95/ISA-88 for handling end-to-end integration, automation and communication between management and control systems [13,14], considering that the implementation of an architecture that supports n MES with microservice scenarios for SMEs is possible [15]. However, its classical structural characteristics make it depart from a distributed architecture, i.e., flexibility is limited for the integration of emerging computing ITs [16]. To mitigate these issues during a precise and robust industrial scaling, it is necessary to have an architectural reference framework that plays a guiding role for the integration of advanced technologies into modern industrial infrastructures, thus achieving a roadmap for digital transformation [17,18].

1.2. Technologies and Frameworks for Scalability Towards Industry 4.0

According to [19], scaling from I3.0 to I4.0 is feasible, compatible and implementable with any of these reference frameworks: Smart Grid Architecture Model (SGAM), Industry 4.0 Architectural Reference Model (RAMI 4.0) and Industrial Internet Reference Architecture (IIRA), but it is crucial to deepen applied research in the different domains that constitute these references so that new challenges and solutions will emerge. In addition, Reference [20] emphasizes that the synergy and implementation of modern and advanced technologies for manufacturing 4.0 are essential, such as manufacturing execution systems (MESs) [21], fog computing systems [22], cloud computing systems suitable for enterprise resource planning (ERP) applications [23], cognitive digital twins (CDTs) [24] and all those technological pillars that fit along the entire value stream of production 4.0. In keeping with this, techniques and practical approaches from other studies were investigated to provide insight into the integration of advanced technologies in a classical industry for scaling up to I4.0 and also under a RAMI 4.0 framework. Under an SRL, there are integrated technologies such as digital twins (DTs), data management in an ERP system, roadmaps and service design methodologies; however, there are issues that have not been investigated such as security and ensuring that the required infrastructure and technologies are well integrated. Reference [25] mentions in the review article that there is no clear and uniform definition of what digital twins (DTs) are, especially in the context of referential models, to ensure a coherent understanding and application in industrial digitization; in addition, [26] proposes the development of ontologies and knowledge graphs of DTs. Reference [27] supports RAMI 4.0 as a guide for the implementation of an IBPT concept that integrates ITs and OTs such as a service-oriented architecture (SOA) and the use of the OPC UA standard, together with advanced augmented reality (AR) and natural language processing (NLP) interfaces, in a simulated production environment, although its implementation complexity and dependence on a robust infrastructure could limit its applicability in certain industrial contexts, such as MSMEs or SMEs. Likewise, in [28], the authors scale an I3.0 to I4.0 SME company based on the reference model guide when implementing a machine–human interface (HMI) in the production line, in order to digitize the acquisition of production data and integrate them into an ERP (enterprise resource planning) system. On the other hand, Reference [29] developed a platform under the RAMI 4.0 reference model for a user to visualize and manipulate the systems and processes of Industry 4.0. These services were constituted by means of a service-oriented architecture (SOA) and the OPC UA communication protocol. Reference [30] make it clear that the applicability of a referential model in a real industrial environment can provide a clear roadmap towards digital transformation. Despite this, their evaluation methodology noted that the successful implementation of the standards covered by the reference model is complex, due to the availability of limited technological infrastructure, investment in new technologies, training of skilled personnel and organizational adaptation.

1.3. Implementation Proposal

In response to the need to integrate and scale advanced technologies within the RAMI 4.0 framework, this article contributes by presenting a case study in which a 3.0 industry was successfully transformed into a 4.0 industry. The highlights of this article are as follows:

- The proposed MES is responsible for controlling in-plant production, sourced from a cloud computing cloud service infrastructure, which stores and manages user data or requests through a web interface.
- This study demonstrates the convergence of a fog computing system in MES for cloud resource provisioning and container orchestration to fog slave nodes located at different stations and sub-processes within a modular production system.
- Through rigorous evaluation and validation, this study demonstrates that the reference model framework guide was key to establish a scaling from Industry 3.0 to Industry 4.0 by integrating and implementing different emerging technologies.

The manuscript is designed to provide a comprehensive overview of the development and validation of the transition from Industry 3.0 to Industry 4.0 in a manufacturing process, based on the reference model framework for the integration of fog computing in a distributed MES. Section 2 examines the advantages and limitations of current technologies, setting the context for the approach presented in our research. Section 3 describes the design and integration of manufacturing execution systems, as well as both traditional and emerging computational technologies, including those that form the pillars of Industry 4.0, ITs, OTs and end-to-end communication systems. Section 4 evaluates the performance of the scale-up implementation compared to the original owner's plant, highlighting its flexibility, scalability, optimization and process effectiveness. The discussion in Section 5 analyzes the results obtained, highlighting the advantages of scaling an industrial system within the RAMI 4.0 framework, addressing possible limitations and proposing areas for future research. Finally, the conclusions (Section 6) synthesize the key findings of the case study, highlighting the potential impact of integrating advanced technologies into modular production processes and suggesting future research directions to deepen the technologies and methods employed.

2. Literary Review and State of the Art

In this section, we present a systematic literature review of the Reference Architecture Model for Industry 4.0 (RAMI 4.0), a comprehensive framework designed to guide digital transformation in industrial systems. The review was conducted under a structured and replicable approach, in academic databases such as SCOPUS, IEEE, Crossref, Elsevier, ProQuest and ResearchGate, prioritizing current research studies to ensure the timeliness of the results. Initially, we analyzed several review articles to build a state of the art that integrates key concepts and definitions for this study. For the literature review, we employed the Scopus Search Analyzer using keywords related to the central themes of our study and their scientific production in recent years: the integration of Industry 4.0 technologies, methodologies, frameworks, challenges and solutions faced by industries during the digital transformation. The final selection of articles was made through an exhaustive filtering by topic and relevance, comparing the approaches and contributions of the papers in each search. With this methodology, we sought to provide a detailed and informed review of the topic.

Subsequently, we assessed the scientific production on Industry 4.0 but lacking a defined frame of reference, which could affect the robustness of the research. In this context, we observe how RAMI 4.0 is gaining relevance in scientific production because it serves as a guide for studies in this area. We further explore how this framework model facilitates the integration of key technologies, such as cyber–physical systems (CPSs) and digital twins. Finally, we examine the methodologies that complement this reference model, the challenges of its implementation in various industries and the solutions developed to address them.

2.1. Literary Review

During a bibliometric analysis of the results on Industry 4.0 and those keywords derived from it and from a source of scientific knowledge such as Scopus, a positive slope was observed from 2018 to 2021, indicating conceptual theoretical frameworks and partial or total implementations within industrial processes, reaching a very considerable number of publications on the topics derived from Industry 4.0 between 2022 and 2023, driven by the enthusiasm to improve manufacturing productivity with digital transformation in the use of emerging advanced technologies, indicating that there is an assimilation of knowledge for semantic network formation and structured information models. Despite this, during the year 2024, there has been a sharp drop in the number of publications, which contrasts with the philosophy of the provision of a smart manufacturing industry, but above all, this is supported by some standardized reference frameworks, which are understood to be a key factor for the implementation of the real Industry 4.0 [31]. In this context, a bibliometric analysis was conducted on the results related to RAMI 4.0, revealing that the number of publications is significantly lower, representing less than 1% compared to publications on Industry 4.0. This finding suggests that, despite the increasing attention given to Industry 4.0, the lack of a guiding framework has not been sufficiently addressed in the academic literature [32].

In order to achieve the scale-up from a traditional Industry 3.0 to Industry 4.0, these researchers [33] created the Agri-4-All framework by integrating advanced technologies such as IoT, blockchain (which ensures immutable and transparent records in the agricultural supply chain) and smart contracts (which automate processes and transactions without intermediaries, ensuring compliance) in a way that is consistent with Industry 4.0 standards, represented in the reference model, validating its contribution through metrics of transparency, security and efficiency in the supply chains of an agricultural production plant, using tomato cultivation as a case study. Likewise, in [34], they take the reference model framework as a reference and structure an organization and data management system in an automotive plant that operated manually. In such conditions, they integrated into this structure a DT conformed to predictive algorithms and AI systems for the optimization of production processes, thus guaranteeing flexibility. On the other hand, for the interoperability of the system, they handled standards such as OPC-UA and AutomationML communication protocols. In contrast, Reference [35] mentions that there is a gap between the conceptual reference architecture RAMI 4.0 and the practical implementation of Industry 4.0 processes; in such a situation, they scale an Industry 3.0 two-stage gearbox process, for which they integrate technologies such as physical assets of the plant (sensors to capture data in real time), integration of physical assets into a digital environment (data collection and processing) and an IT infrastructure that allows the exchange of data between the different components of the system. It also models and simulates the behavior of physical assets, allowing decision-making based on real-time data, and finally manages the models and simulations according to business objectives. This entire situation was feasible before the implementation of digital twins and a middle-tier architecture, which allows these theoretical models to be put into practice and in different technological configurations: cloud, edge computing and hybrid combinations of both technologies. From another point of view, in [36], it is mentioned that as factories and manufacturing systems become digitized, the integration and harmonization of large volumes of data from different standards become a critical challenge for Industry 4.0. In such a case, the researchers use a methodology that integrates natural language processing (NLP) and knowledge graphs (KGs) to improve interoperability between standards, identifying and resolving semantic conflicts (SICs).

Within the research methodologies and conceptual macros, Reference [37] proposes a detailed conceptual framework that facilitates the transformation of smart production planning and control (SPPC) systems by integrating the classical functions of a production planner and control (PPC) with emerging technologies such as IoT, CPS and digital twins, but also provides a roadmap for the adoption of RAMI 4.0 axes. However, as we indicated at the beginning of this section, the lack of concrete case studies or detailed practical implementations limits the immediate applicability of the framework in real-life situations. This is why, although the document offers a systematic and theoretically sound structure, it is not supported by comprehensive simulations or practical validations, indicating that its contribution is mostly conceptual. The authors of [38] created an additional layer based on RAMI 4.0, i.e., they added flexibility to an environment where batch customization and customer satisfaction are increasingly crucial for commercial success, thus managing customer outcomes in smart manufacturing. This was made possible through an IoT system that integrates with blockchain in an IOTA network for handling microtransactions. Instead of ensuring ubiquitous connection, they employ OPC UA; they mention the use of artificial intelligence algorithms and Business Process Management (BPM) for production optimization based on customer-expected outcomes. On the other hand, Reference [39] mentions that there are intelligent systems where their processes operate independently, and therefore it is essential to manage them throughout their lifecycle by means of a system of systems (SoS). With this contribution, the researchers seek to improve interoperability and process optimization through a service-oriented architecture (SOA) for effective orchestration between multiple multi-stakeholder parties. Following this line on the integration of advanced technologies, Reference [40] studied the possibility of integrating Model-Based Engineering (MBE) with Industry 4.0, using Deep Learning and IIoT, with the situation managed by Recurrent Neural Networks (RNNs) on a Software Platform Embedded Systems (SPES XT), thus improving decision-making and task allocation and achieving improved efficiency and cost reduction in the RAMI 4.0. It should be noted that it is an innovative methodology and the study demonstrates the effectiveness of its proposal through simulations and theoretical models; however, it is not clear if an implementation and validation has been carried out in some kind of real industrial plants.

The literature review identifies several challenges and proposed solutions that researchers report, such as the case of [41], which developed a specific methodology for SMEs that guides the implementation of referential models, finding different challenges such as the correct implementation of referential models in SMEs, the need for modernization of equipment to comply with communication standards, the lack of resources and technological maturity, the complex integration of new technologies with existing systems and the lack of standardized methodologies. To address these challenges, the researchers proposed a proof-of-concept (PoC)-based methodology to validate solutions at each layer of RAMI 4.0, using an iterative and flexible approach that allows for continuous adaptations. Reference [34] also states that, despite its comprehensive nature, the referential model faces challenges in practical implementation due to a lack of formalization and standardized methodologies. Efforts to address these challenges include the development of the reference model toolbox, which provides a step-by-step guide for model-based production systems engineering. In this context [42], based on the reference model, the study proposes an architecture that enables vertical and horizontal integration of the value chain, exemplified through a use case in the automated production of personalized juices, the main challenge being the need to ensure interoperability and seamless communication between the different systems in the value chain, especially when dealing with historical and real-time data; thus, a service-oriented architecture (SOA) that uses microservices and Asset Brokering Manager (ABM) to maintain a data flow between the flat and the cloud was employed. On the other hand, in the Moroccan industry [43], the researchers discover challenges such as integration with legacy systems, data management and privacy, cybersecurity risks and the acquisition of specialized talent, especially in the context of an emerging country like Morocco. In this context, the researchers present a simplified methodology to deploy Industry 4.0 technologies; that is, they show a structured framework that guides companies, especially in emerging countries, in the effective adoption of industrial digitization, optimizing processes, predictive maintenance and performance management. Starting with the digitization of assets and improving interoperability between systems by implementing SCADA and real-time data analytics, they incorporated predictive maintenance and performance management technologies to optimize operational efficiency, used Hadoop (Cloudera) as a data storage platform to handle large volumes of information and used MQTT/DSS for data management and transfer. Its validation was through proof of concept (PoC), where technology solutions were implemented and tested in a controlled environment before full deployment.

While RAMI 4.0 provides a robust framework for digital transformation in manufacturing, its implementation can be complex due to the diverse nature of industrial systems and rapidly evolving technology. The success of the framework depends on continuous adaptation and the development of complementary methodologies to address industry-specific needs. As industries continue to embrace digitization, the referential model will play a crucial role in guiding the integration of emerging technologies and ensuring the interoperability and efficiency of industrial systems.

2.2. RAMI 4.0 (Reference Architectural Model Industry 4.0)

RAMI 4.0 is a three-dimensional reference model that organizes and structures the key elements of Industry 4.0, facilitating integration and interoperability between industrial and digital systems. This model covers aspects from physical assets to business processes, including communication, information management and function orchestration. The referential model enables industrial systems to evolve towards more flexible, scalable and adaptable architectures, supporting the transition from traditional plants to smart and connected environments. In an Industry 4.0 project, the adoption of reference model ensures that all components, from plant hardware to cloud services, are aligned and operate cohesively to achieve the goals of efficiency, quality and resilience.

The Architectural Reference Model for Industry 4.0 is illustrated as a three-dimensional cube that integrates all key aspects necessary for the implementation of Industry 4.0. This model is organized along three axes: the hierarchical axis, the layer axis and the lifecycle and value chain axis. The hierarchical axis, based on the IEC 62264 [44] and IEC 61512 standards [45], runs from the 'Product' to the 'Connected World', representing different levels of the automation hierarchy, from field devices to cloud integration. The layer's axis spans six levels: Assets, Integration, Communication, Information, Functional and Business, each detailing a crucial aspect of industrial systems, from physical components to business processes. The lifecycle and value chain axis, supported by the IEC 62890 standard [46], considers the phases of development, use, maintenance and, finally, decommissioning of a product or system, dividing these phases into 'Types' and 'Instances'. 'Types' are associated with the development and use/maintenance stages, representing general or abstract definitions of a component, such as templates or theoretical models. On the other hand, the 'Instances' relate to the production and use/maintenance stages, indicating the concrete and specific implementations of these models in reality, for example, a particular device in operation in a factory, i.e., these phases allow the model to cover both the theoretical design phases and the practical implementation, facilitating the management of the complete lifecycle of products and systems within the Industry 4.0 environment [35].

Despite this, it must also be said that the RAMI 4.0 reference model does not elaborate how the parts within this complex solution space are interconnected and interact, nor does it consider the different actors involved, who may sometimes have conflicting interests. In other words, it is not clear how the new generation standards can implement a data-driven architecture (Digital Thread) that links the information generated throughout the product lifecycle.

In Table 1, a synthesized view of the technological approaches in Industry 4.0 is shown, facilitating a clear and quick understanding of their advantages and limitations without requiring an exhaustive analysis of each source. It also highlights the strengths where it introduces innovations or solves common problems in previous research, thus allowing a better contextualization of its relevance in the field.

Table 1. Comparison of technological approaches in Industry 4.0: advantages and limitations.

Ref.	Proposed Topics	Main Advantages	Challenges and Limitations	Added Value with the Implemented Study
[33]	MES in Industry 4.0	Synchronization of stations and real-time management	Limited integration with external systems	Expands interoperability with IoT and FC
[34]	Hybrid SOA-MES	Real-time connection with advanced services (AI, data)	Implementation complexity in SMEs	Flexible architecture facilitates adaptation
[35]	Fog Computing (FC) in MES	Reduced latency, fast real-time response	Requires robust infrastructure	FC and MES operating on multiple levels simplify infrastructure and distribute loads
[36]	RAMI 4.0 with IoT and Blockchain	Data security and transparency	High integration costs	Connectivity benefits at a lower cost
[37]	Digital Twins in Automotive Plant	Flexibility and advanced simulation	Requires extensive database	Local and cloud data handling reduces complexity without using DT
[38]	ISA-95 in Industry 4.0 Environment	Efficient task management and scalability	Limited interoperability with new technologies	Improves interoperability with FC and IoT
[40]	OPC UA in Industrial Communication	Standardization of protocols	Requires robust and constant network	Node-RED enables flexibility without constant network dependency
[41]	Fog Computing for Manufacturing	Network resilience and continuous processing	Requires trained personnel	Eases I4.0 operations for SMEs
[42]	SCADA and Big Data Integration	Real-time data monitoring and analysis	Complexity in SCADA data management	Use of local databases reduces complexity
[43]	HMI with ERP in Production Line	Data digitization and traceability	Limited configuration flexibility	MES facilitates customizable configurations

2.3. MES (Manufacturing Execution System)

A manufacturing execution system (MES) is a comprehensive software solution that manages, monitors and optimizes production operations in real time within an industrial plant. This type of system enables efficient workflow management, synchronizing the different production stations and ensuring the quality and consistency of the final product. In the context of Industry 4.0, MES becomes a central component for integrating plant automation with advanced data analysis and decision-making services, facilitating the connection between the plant and external systems such as the cloud. In addition, the incorporation of technologies such as FC and the allocation of specific resources within the MES allow critical and distributed tasks to be handled, improving responsiveness and operational efficiency [47]. On the other hand, and with the objective of providing an integral solution for the management of industrial processes in an Industry 4.0 environment, it is highlighted that a hybrid SOA-MES integrates the flexibility and modularity of a service-oriented architecture (SOA) with the operational capacity and real-time control of an MES. This hybrid approach allows plant operations to be connected and coordinated with advanced cloud services such as data analytics, artificial intelligence and critical information storage. The SOA facilitates communication and interoperability between different distributed services, while the MES ensures that plant operations are managed efficiently and without disruption. This type of architecture is especially useful in industrial environments where the combination of local control and cloud services allows for greater flexibility, scalability and resilience in the face of changing conditions and increasing demands [48].

2.4. Fog Computing (FC) System

FC is a computing paradigm that extends cloud services to the edge of the network, closer to data sources such as sensors, IoT devices and control systems in industrial plants. Unlike traditional cloud computing, where data are sent to centralized data centers for processing, FC allows processing, analysis and decision-making to take place closer to where the data are generated. This reduces latency, improves operational efficiency and enables faster real-time response, which is essential in dynamic, mission-critical industrial environments. In an FC architecture, fog nodes act as intermediaries between field devices and central processing or storage systems in the cloud. These nodes can be devices with intermediate computational capabilities, such as routers, gateways or small local servers, that execute specific tasks, such as processing data, filtering information or running artificial intelligence algorithms. In doing so, they offload the workload from the cloud and allow applications to run continuously and efficiently, even in environments with limited or intermittent connectivity [49].

FC is an extension of the cloud computing model, bringing computational resources closer to the edge of the network, where data are generated and used. In a manufacturing system, FC acts as an intermediary between plant floor devices (such as sensors and actuators) and cloud services, enabling local data processing, task orchestration and real-time decision-making. This approach is particularly valuable in environments where latency, connectivity and workload are critical factors. Implementing an FC system in the context of an MES allows for efficient distribution and management of computational tasks, ensuring that shop-floor processes run optimally, even in unstable network conditions or under high demand.

3. Materials and Methods

This section details the procedures, aspects, experimental and methodological settings used in the research. This study focuses on scaling up from Industry 3.0 to Industry 4.0 based on a reference framework that is a guide for the implementation of disruptive technologies that contribute to the improvement of production and operational management in real time. To this end, the plant has a modular production system that is used in educational and research environments to emulate FESTO's automated manufacturing processes (MPS) 500. In addition, the MES runs a simultaneous management of automated processes in the plant and its load distribution and also allows the flow of abstract bidirectional information arranged in the cloud. On the other hand, a cloud infrastructure provision is available for the management of batch order requests by users. The whole length of the above mentioned value chain can be shown in a general way based on the classical automation pyramid or from three representations arranged in levels 0–2 for edge devices, level 3 for plant control and level 4 for enterprise, a situation that becomes possible because model architectures like IBM 4.0, IIRA and RAMI 4.0 are based on the ANSI/ISA-95 reference model, especially in the functional layer [50,51]. However, the purpose of this research is to scale an industry-focused approach to plant floor production management, station synchronization and process orchestration using near edge and cloud computing. In such a context, a set of five MPS in-line manufacturing production stations, equipped for wireless connection and connectivity with an MES, is based on a hierarchically distributed architecture, which allows it to also operate as a master fog computing (MFC) node for in-plant processes. The information flow is bidirectional throughout the architecture under the Message Queuing Telemetry Transport (MQTT) protocol, allowing MES connectivity with an infrastructure that provides cloud services for the provision and backup of order request information stored in a database (see Figure 1). In this situation, the user experiences transparency during his order request because the web service updates the products that are in stock in real time from the shop floor.

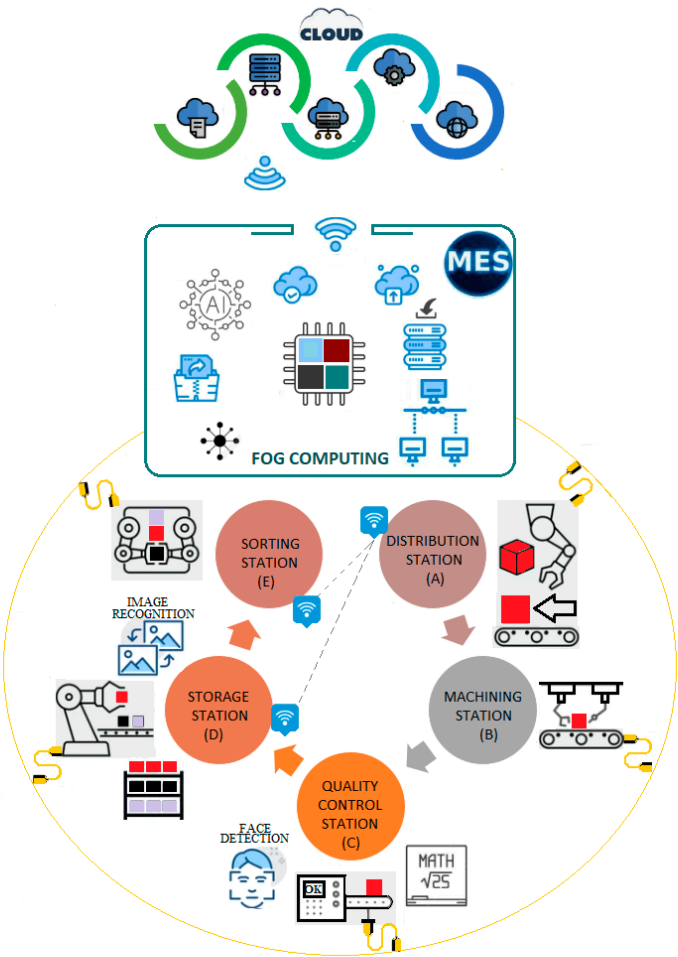

Figure 1. Functional architecture for the control and management of batch manufacturing processes.

According to [52], one of the strategies to avoid technological obsolescence is to have modular systems focused on key technologies, allowing the integration of recent advances without the need to replace the entire system, optimizing resources and ensuring compatibility despite the heterogeneity of devices involved in an escalation. In this sense and starting with the MPS, different technologies were integrated through the different circumstances of the implemented architecture. In the following subsections, the elements, experimental arrangements and methodological techniques involved in the scaling up to Industry 4.0 under the guidance of RAMI 4.0 will be detailed.

3.1. Work Center and Its Modular Production Stations

The MPS has different modular in-line production stations (distribution (A), machining (B), quality control (C), storage (D) and sorting (E)), which communicate through the ASI communication protocol arranged along the entire pallet conveyor belt route. Each station is controlled by a PLC S7 300 programmable logic controller, manufactured by Siemens AG in Munich, Germany, except the quality control station, which is strategically controlled by an embedded card. With these features offered by the MPS, the synchronization of the production plant is defined according to business requirements, as is the restructuring of the original production process for the incorporation of new technologies (see Figure 2). In the following, the manufacturing of different colored parts is described:

- When a user requests a mini batch order from the web server, the objective is to dispatch what has been requested, so station (D) starts by selecting the products from the warehouse and placing them on pallets, transporting them to station (E) for their classification by color (red, black or silver).
- Once the order is completed, the production line starts immediately from stations (A)-(B)-(C)-(D).
- In case there is any defective product on its edges and it does not meet the quality conditions of the product, the piece is sent directly to station (E) to be classified as scrap.
- In station (C), a functional reconfiguration of the process is made, which means that it will not only execute the quality control process but also, arbitrarily, two additional processes will be carried out: one for the recognition of personnel by face and another one for the resolution of a calculation. This means that this station does not have a PLC for these operations but works by means of embedded cards that operate as distributed nodes within the FC system.

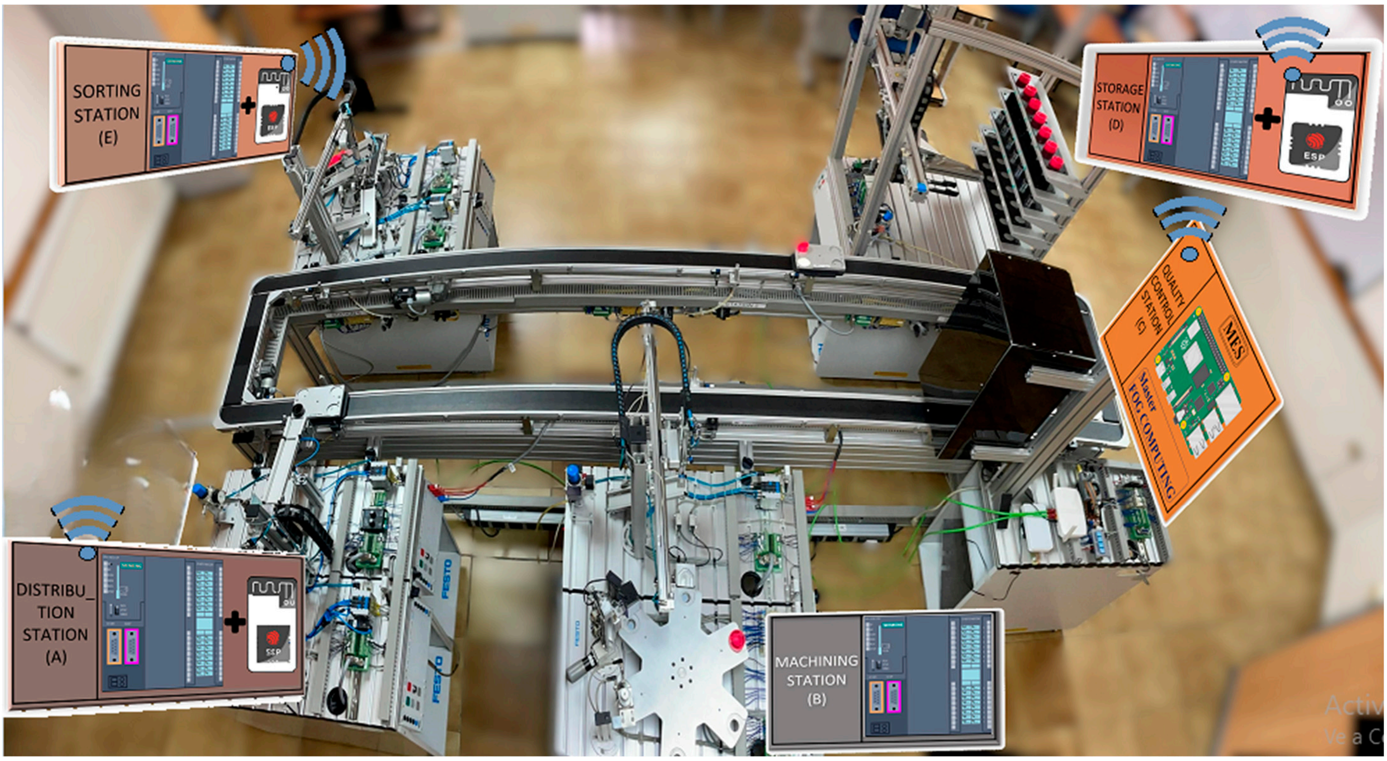

Figure 2. Enabling digital connectivity and control of a modular production system (MPS-500) from FESTO.

3.2. Integration of Legacy Devices via Wireless Intermediaries

During the characterization of the workstations, the control devices were categorized as legacy devices for scaling to Industry 4.0, because they lack Wi-Fi or Ethernet modules, complicating the objective of connection and connectivity with the MES in terms of manufacturing process management. For this reason, these legacy devices are updated to operate within an IoT environment and with MQTT protocol; that is, the PLCs of stations (A) and (E) were equipped with an ESP32 card to operate as clients within wireless local area network (WLAN) Wi-Fi 802.11 b/g/n/e/i, and as an access point (AP) to the MES, an ESP32 master card was added in station (D).

3.3. Advanced MES for Hybrid and Multi-Level Integration

SMEs that wish to implement advanced technologies face different significant challenges. In this context, the research proposes to address the integration of advanced technologies, the use of low-cost control units and internal reorganization to adapt to the new productive dynamics. In this context, it is proposed to develop a solution that addresses these issues, converging in the same control unit, concepts, methodologies and operations for parallel and concurrent work in a multi-level scenario.

Figure 3 shows the MES architecture implemented on a Raspberry Pi 4 B development board, with a 1.5 GHz quad-core processor, 4 GB RAM and 802.11ac Wi-Fi. This implemented structure demonstrates that the MES can be deployed at different hierarchy levels, giving it flexibility to manage process overloads in the plant while ensuring interoperability between the plant and cloud endpoints. In this context, the key features that this architecture offers for intelligent manufacturing management are described below: (a) It constantly ensures the connection to the cloud. (b) It enables bidirectional information flow with the cloud service infrastructure via Node-RED as a client and an MQTT (mosquito) broker. (c) It has a local database, which, via MySQL, allows recording order requests as a backup in case of internet service provider (QoS) failure. It also manages the information table that synchronizes stations (D) and (E), responsible for dispatching requests, and stations (A, B, C, and D), responsible for replenishing parts. For this, it uses as key data the position of the parts for dispatch and their color for replenishment (see Figure 4). (d) It establishes a bidirectional communication with the ESP32 master located at station (D), which notifies it every time a part is removed, updating the information tables. This allows the local database to efficiently organize the replenishment process for each dispatched part.

In Figure 3, the hierarchy levels at which the MES can operate are presented in different shades, highlighting how the AI and FCM processes run on different instances of the same processor. The first process, together with the other top-level tasks described in the previous paragraph, are managed on one instance, while the second process is executed on the remaining instance of the same board, allowing for an efficient distribution of resources.

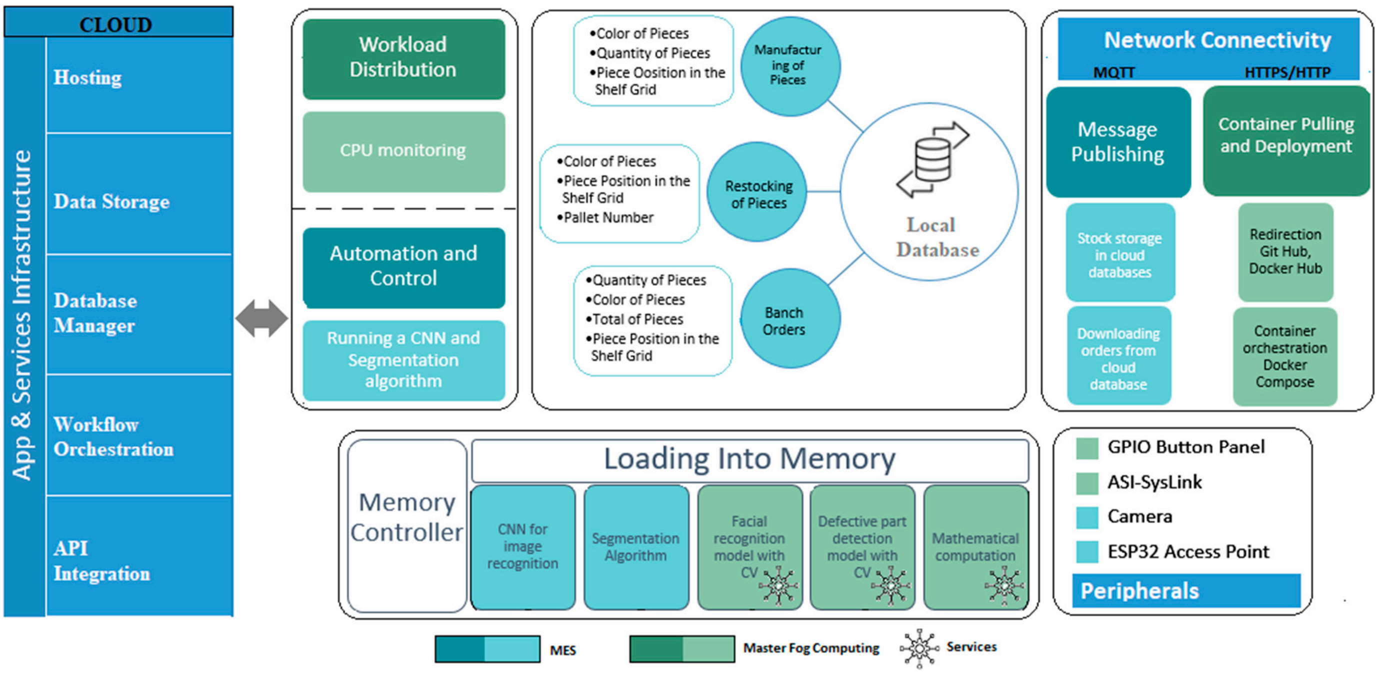

Figure 3. Modular microcomputer architecture for multi-level management, integrating plant data, local storage and cloud services.

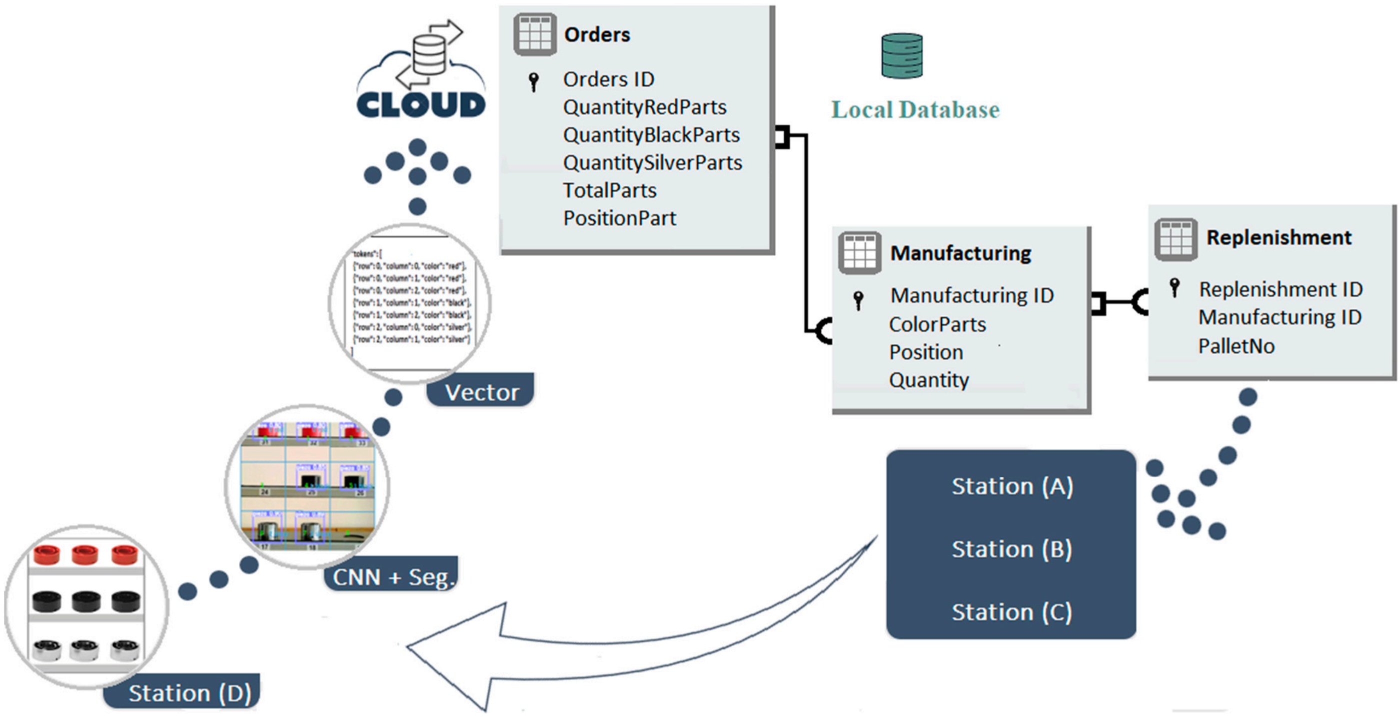

Figure 4. Cloud-based production and warehouse management system and local database for stock and order control.

3.3.1. Stock Management and AI in the Production Process

The token replenishment process at station (D) is performed in such a way that each warehouse rack is matched with a characteristic color of the piece. On the other hand, each time the dispatch process is completed, an image of the current situation of the warehouse is automatically captured by means of a 720p HD webcam for the execution of an object detection model in real time using YOLO v5 convolutional neural networks (CNNs), and then a segmentation algorithm is applied to precisely delimit the space corresponding to each detected piece and thus know its position within a matrix that is generated in the image (see Figure 4). These data are sent to a web server where this information is stored and managed, so that a user can see in real time the number of pieces per color that the manufacturing company has in stock. Meanwhile, in the plant, the MES manages the process of replenishment of cards, and at the same time, another user can place a new order, in which case the MES automatically downloads a vector template of the requested order, which indicates the position of the piece that corresponds within the matrix and consequently its color, thus maintaining a continuous and orderly flow of processes and synchronizing the replenishment and dispatch of colored pieces.

3.3.2. Fog Computing and Algorithms for Production

One of the main challenges identified in the literature review was the high costs associated with the hardware infrastructure, which represents a significant barrier for SMEs. In this regard, the performance limitations involved were taken into account when selecting a control unit capable of operating efficiently within an MES. For this reason, experimental tests were carried out to interpret the thermal behavior of the CPU once the aforementioned features and technologies were included. During the complete execution of the production processes (D)–(E), (A)–(B) and (D), the average temperature was approximately 78 °C. According to the technical specifications of this board, in cases of high workload, its temperature can reach 85 °C, and consequently, the CPU would automatically reduce its performance (throttling) and possibly cause interoperability problems between the plant and cloud. Considering the resources available on the embedded board, and that during the experimentation, no task was executed on station (C), we decided to develop an FC system that converges with the MES for parallel operation, i.e., an MFC manager is added, which remains on the main board, while the additional loads generated by the execution of three algorithms are distributed between two FCS nodes, thus relieving the load on the main node and avoiding possible lag to the other processes under the responsibility of the MES. The algorithms that were developed at station (C) are described below:

- In this study, a computer vision system was implemented to control the quality of the parts leaving station (B), for which the Cascade Trainer program and the OpenCV library in Python were used. A model was trained with positive images (containing the part) and negative images (environment without the part) to recognize objects through cascade classifiers. In addition, the HSV color space was used for color detection, and the Canny algorithm was used to identify edges and contours in the parts. The system was able to distinguish good and bad parts based on contour analysis and the conditioning of a tolerance range. Parts that did not meet this criterion were classified as defective and separated at station (E).
- Next to station (C), there is a facial feature biometric, which is executed when an operator requests, by means of a button panel, to enter a certain site. In such a way, the facial recognition algorithm based on the dlib library uses a set of advanced techniques for face recognition. Its main components include a face detector that employs the HOG (Histogram of Oriented Gradients) method and CNNs, such as ResNet-34, for the identification of facial regions. Once the face is detected, dlib extracts 128 specific landmarks from the captured image. These landmarks are compared with those previously stored in the dataset using a Siamese neural network that processes pairs of images to measure the similarity between them. When a fairness equivalence is reached, the corresponding biometric face is identified.
- To cause the MES to overload and the FC system to run, a program that calculates the square roots of ten thousand random numbers was intentionally added. The process is triggered when an operator presses a button, starting the execution of the program, which begins by importing the multiprocessing and math libraries. Then, the function 'worker' is defined, which calculates the square roots of a range of numbers. By means of a condition, the execution time is prioritized over the total completion of the process in order to perceive the results during the experimental tests.

Master fog computing (MFC) orchestration process: The expansion of the processes in station (C) resulted in a control migration (retrofit) from a PLC S7 300 to an embedded card, which has the operating characteristics shown in Figure 3. In this context, when the system starts for the first time, it proceeds with the provisioning of cloud services, and the images are stored in a memory space of the embedded board for later management, i.e., the MFC node operates through Docker Hub, obtaining containers based on algorithms hosted in a local GitHub repository which are then run with Docker Compose. The algorithms are computer vision for the identification of malfunctioning parts, computer vision for facial detection, a computation algorithm and a tool for system monitoring (Node Exporter). The latter is useful to determine from the MFC the maximum percentage of operation of the CPUs of the FCS nodes; in this way, the amount of processes to orchestrate is also managed and consequently the threshold temperature of operation is not exceeded.

Connectivity: To start the provisioning operation, the MES maintains a communication flow with the web server client in AWS through MQTT, so from the MES, a request is sent to Node-RED, which acts as an intermediary and makes a query to GitHub through an HTTP request (images from Docker Hub), with the local address of the repository. The intermediary notifies the MES, indicating that it can start the provisioning process. From here, MFC uses Docker Compose's own yml read file to manage the download of the images from Docker Hub, bypassing the web server on AWS to reduce latency in the process.

On the other hand, the MFC also communicates with the MPS stations within the ASI network to receive or transmit digital signals as indications for the execution of the modular production process of the station before and after it, i.e., station (B) indicates to station (C) that the quality control process should begin, then station (C) indicates that the part is in good condition for storage station (D), or if the part is defective, it indicates to station (E) to scrap that part. This communication is carried out by an ASI SysLink connector and a voltage-level matching circuit.

3.4. A Comprehensive IoT Management System in the Cloud

Within the process of scaling up the MPS to Industry 4.0, web content for remote users to the plant was also provided, allowing them to request their orders according to the stock available on the production floor; this means that efficient data flow and proper management of traffic through necessary ports must be ensured. For that reason, an infrastructure of cloud services was assembled, starting from an AWS computing resource, specifically the Elastic Compute Cloud (EC2), to which several services were added such as an MQTT broker (Mosquitto) that acts as a 'topic1'-specific channel communication intermediary with the MES over port 1883, allowing AI (warehouse stock) results to be processed and organized via Node-RED over port 1880 to the MySQL database. At this point, and through port 80, a user can send an HTTP request to the Apache server, and it provides the phpMyAdmin web page, allowing the user to query the database, for example, to view the stock of parts available at station (D). At the moment, when the user requests a production order, the database is updated, and Node-RED is waiting to extract the information in vector form when the MES requests that specific dispatch channel, as seen in Figure 5.

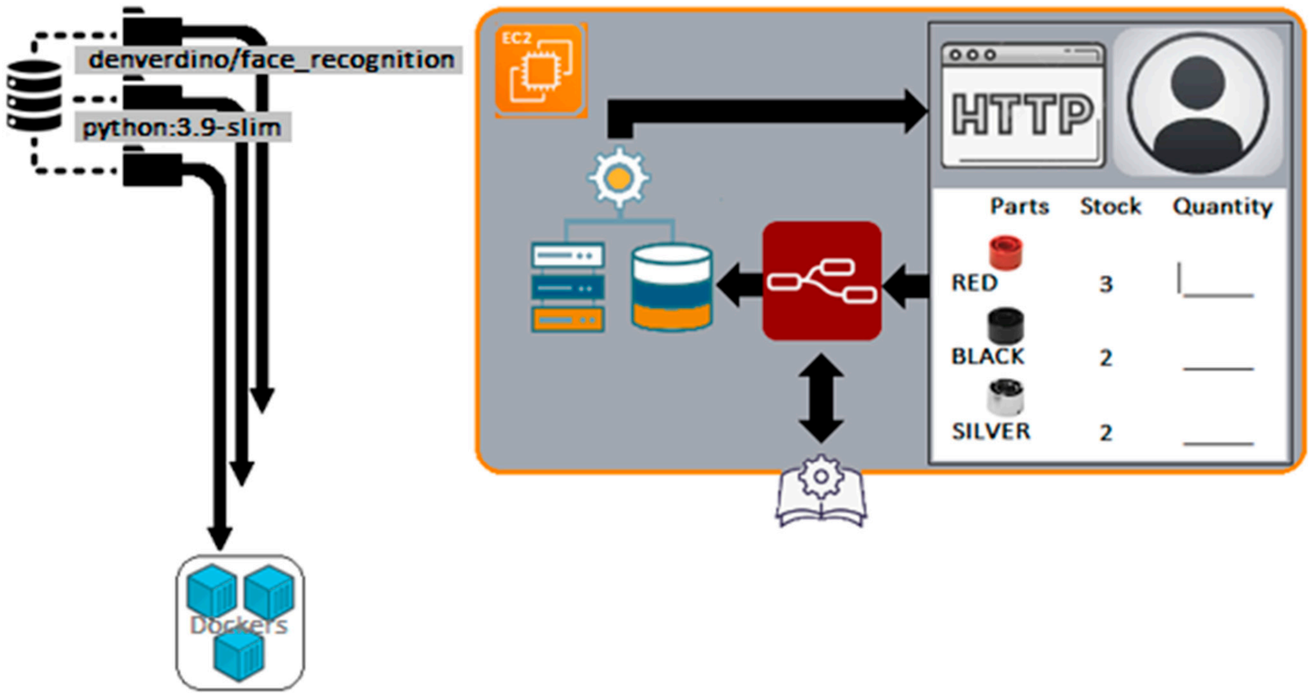

Figure 5. Cloud infrastructure for remote order management in the MPS with integration of cloud services and communication via IoT protocols.

3.5. Assessment of the Transformation from Industry 3.0 to 4.0 According to RAMI 4.0 Architecture in the Cloud

RAMI 4.0, as a reference framework in Industry 4.0, organizes the elements and functionalities of a smart plant in a three-dimensional structure. This cube has three dimensions: one for the lifecycle and value stream, one for the hierarchy of levels and one for the functional layers (see Figure 6). By contextualizing these concepts in the implemented work, it shows how different levels and layers of the reference model are adaptable to the practical needs of the plant, the implemented MES and the IoT-based Integrated Cloud Management System.

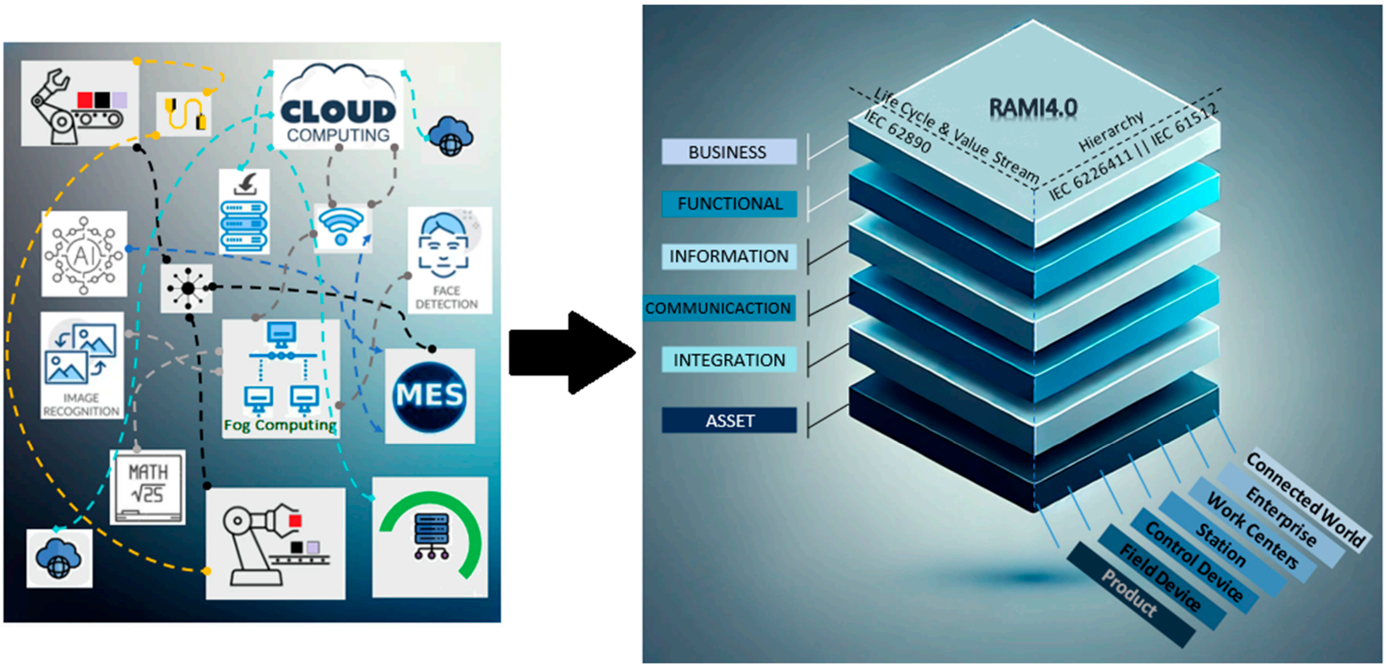

Figure 6. Transition from an unstructured environment to RAMI 4.0 architecture.

3.5.1. RAMI 4.0: Hierarchical Layers in Implementation

The hierarchical layers of RAMI 4.0 (Assets, Integration, Communication, Information, Functional and Business) are shown in this project, highlighting the transformation of a conventional production plant into a smart and connected environment:

Asset layer: Here, the physical and virtual elements are identified. On the one hand, the plant includes the S7-300 PLCs that control the storage, sorting and distribution stations. The quality control station is controlled by an MPU card, which operates in parallel, while virtual assets such as computer vision algorithms and cloud services are managed by the MES. The integration of legacy technologies with new solutions, such as the installation of ESP32 for wireless communication with the PLCs, enables the convergence between the physical and the digital in the manufacturing environment.

Integration layer: The interaction between the different components is realized through recent technologies. For example, ESP32s are used as wireless intermediaries for connecting legacy devices (PLCs) to the MES, while Node-RED orchestrates the communication and data flows between the MES and cloud services. This layer ensures that physical and virtual assets interact in a coordinated manner, thus enabling synchronization between the MES and the cloud.

Communication layer: The architecture implements communication protocols such as AS-i to coordinate stations within the plant and MQTT for connection with the cloud; this protocol also allows synchronization and coordination between the MFC and FCS nodes, distributing tasks in the plant according to operational conditions. In this way, critical processes are transmitted securely and in real time, reflecting the information flow necessary for an Industry 4.0 environment.

Information layer: Information is managed and stored both locally and in the cloud. For example, the MySQL database in the cloud stores the orders, while the MES takes care of downloading these data to a local database as a backup. In addition, the system collects data on the CPU load of the FCS nodes, which is used to optimize the distribution of tasks, thus avoiding saturation of the embedded cards. This layer not only ensures the availability of decision-critical data in real time, but also ensures redundancy and operational continuity in case of connection failures.

Functional layer: The functional layer is embodied in the management performed by the MES and the MFC by coordinating the stations within the production operations and distributing the tasks to the FCS nodes, thus automating the replenishment of the warehouse according to the orders. In addition, the FCS nodes run computer vision algorithms for quality control and facial recognition, showing how the functional layer integrates advanced and distributed tasks, optimizing the production flow.

3.5.2. RAMI 4.0: Hierarchical Levels in Implementation

The hierarchical levels of RAMI 4.0, ranging from 'Product' to 'Connection with the Outside World', were associated with the elements and structures of the implemented system:

Product level: In the implementation, this level is reflected in the products manufactured and stored in station (D). The inventory management and the data of each product (position, status) are handled locally and in the cloud, allowing an automated stock management.
Field device level: Using sensors, actuators, PLC S7-300 control devices and ESP32 multi-agents integrated in an IoT network, key signals from stations are captured in the plant. These data are transmitted to the MES to enable real-time production decisions.
Control unit level: Represented by the MES and the FCS nodes, this level is crucial for the control and monitoring of operations. The MFC distributes tasks to the FCS nodes, which execute image processing algorithms and mathematical calculations, and then report the status to the MES. Dedicating a part of the Raspberry Pi 4 B processor to FC operations optimizes performance and avoids interference in the overall plant management.
Station level: This includes the production stations (A, B, C, D and E) and the operations coordinated by the MES. For example, the quality control station uses computer vision algorithms for product inspection, which are managed and synchronized from the MFC.
Work center level: The MES manages and coordinates production operations at the work center level, enabling overall supervision of the production process.
Enterprise level: This level is materialized in the connection to the cloud, where the web services, the MQTT broker and the MySQL database are hosted. The MES receives and processes orders from this cloud, while Node-RED orchestrates the integration with the services. Thus, the company can monitor and control production operations, managing orders and stock remotely.
Connected world level: Cloud services (MySQL, MQTT) and the IoT network connect the plant with external partners, facilitating real-time collaboration through network infrastructure and data sharing in the cloud. This level allows the plant to be connected to a global partner network, achieving real-time interoperability and collaboration, but without spanning the entire product lifecycle.

By contextualizing the layers and levels of RAMI 4.0 in terms of the implemented project, it becomes evident how this work is structured and operates according to the principles of referential models, facilitating the interoperability, flexibility and advanced automation characteristics of Industry 4.0, because the work performed aligns with the reference model framework by integrating its layers of assets, integration, communication, information and functionality to form an advanced MES in Industry 4.0. To synthesize the information, a tabulation of the above contextualization was made to identify the penetration of implementation in the reference model, in areas where implementation is substantially met, partially covered and with minimal or limited implementation (see Table 2).

Despite the coherence and integration of technologies based on RAMI 4.0 for this industrial transformation. The implementation performed focuses on real-time production and operation, leaving some layers and levels of the RAMI 4.0 model not fully addressed. The production and service function layers do not cover after-sales service management or additional product functions, as the focus of the project is operational. Likewise, the lifecycle and value stream layer is limited to the in-plant production phase, not including the design, development or recycling stages. Finally, the business layer is of limited use, as the focus of the project is on technical implementation rather than strategic alignment. Despite these omissions, it can be stated that the implementation follows the principles of RAMI

4.0, and its structure was used as a basis for creating an advanced Industry 4.0 architecture. The methodology and integrated components are in line with what the referential model proposes for many of its key aspects, such as interoperability, flexibility and automation. The lack of full use of certain layers, such as product and service, does not invalidate the relationship with the referential model, as this framework is flexible and adaptable to different industrial scenarios. Therefore, it is correct to say that the work is based on the reference model architecture, using most of its layers and tiers to implement an effective solution aligned with Industry 4.0 principles. However, the Discussion section proposes certain criteria that could be incorporated into this study to cover the missing layers.

Table 2. RAMI 4.0 implementation map in a smart production system.

HIERARCHY LEVELS / LAYERS	**Business**	**Functional**	**Information**	**Communication**	**Integration**	**Asset**
Product	Limited use due to production focus	Process Orchestration: Task orchestration is ensured from production to the final process on the plant floor	Data Management: Critical information on orders and products stored in MySQL	Communication Protocols: MQTT ensures efficient communication between various components	Not specifically applicable	Physical product and its digital representation through digital twins in cloud services infrastructure
Field Device	Limited use due to production focus	Interoperability: FC node and legacy systems like ESP32 enable connectivity	Sensor data on CPU load and temperature of FCS nodes	Synchronization and Coordination: AS-i and MQTT protocols manage synchronization	Technology Integration: Field devices integrate with both legacy and modern technologies	Sensors and actuators that are part of the control system, including FCS nodes and PLCs
Control Device	Limited use due to production focus	Process Orchestration: The process orchestration function ensures efficient management of FCS nodes	Data Management: Controller manages and utilizes data from specific processes	Communication and Coordination: Coordination between MFC and FCS ensures efficient execution	Communication and Connectivity: ESP32 as wireless intermediaries ensure connectivity with legacy systems	Physical and virtual controllers that manage plant production
Station	Limited use due to production focus	Process Automation: Automated stock replenishment at workstations	Data Management: Machine indications and processing data stored locally and in the cloud	Synchronization and Coordination: Efficient communication between stations via AS-i	Technology Integration: Integration of workstations into a cohesive system	Physical assets including workstations like AS-RS, sorting stations, etc.

Table 2. *Cont.*

HIERARCHY LEVELS / LAYERS	Business	Functional	Information	Communication	Integration	Asset
Work Center	Limited use due to production focus	Process Automation: The MES manages integrated production within the work center	Production line indications and data managed by the MES	Communication coordination between work centers and control systems	Technology Integration: Integration of control and production systems	Physical stations and assets interacting within the work center
Enterprise	Limited use due to focus on technical and operational implementation	Process automation at the enterprise level, including quality and production management	Performance analysis and data management across the enterprise via the MES	Design of communication and connectivity infrastructure to support production	Node-RED and other systems for data and process integration across the enterprise	Documentation and management of both physical and virtual assets at the enterprise level
Connected World	Limited use due to focus on technical and operational implementation	Collaborative production as part of a network of partners and collaborative factories	Storage and Backup: Critical information backed up locally and in the cloud	Global management and coordination for production process synchronization	Technology Integration: Connection with external systems and partners	Virtual assets that extend beyond the company, including databases and cloud services

4. Analysis of Results

With the integration of new technologies for scaling up to an intelligent MPS, we proceed with the validation of the system, through experimental tests of batch order requests, i.e., the performance of the MES will be identified when integrated with the plant processes, unexpected failures of the internet service and the plant response to the execution of production orders.

At start-up, the MES executes different instructions in parallel such as connectivity with the cloud, ensuring a bidirectional information flow with the cloud services, preparing the management of SQL queries in the local database, setting up bidirectional communication with the ESP32 master and executing an AI model for the detection and segmentation of parts captured in images at station (D). This system start-up situation was considered to have a slow loading time due to the concurrent execution of these processes on a specific processing space, a situation necessary to update the stock of products in the plant in real time. On the other hand, the performance of the reconnection of the MES with the web server in case of a failure in the quality of service (QoS) of the internet provider was evaluated. To simulate this situation, the internet service was interrupted, and through the cloud connectivity response, the resilience results presented in Table 3 were obtained. In addition, the speed at which data can be sent and received between the web server and the MES, located at the edge of the plant, is detailed.

Table 3. MES assessment: start-up, resilience and data flow.

System Data Flow	
Upload [Mbps]	30.62
Download [Mbps]	69.48
System Resilience	
Reconnection: MES/CLOUD CLOUD/MES bidirectional communication	1.5 [s]
MPS 4.0 Start-Up	
System Start-up Time	32 [s]
Connection: MES/CLOUD-CLOUD/MES bidirectional communication	1.7 [s]
Connection: MES/ESP Master-ESP Master/MES bidirectional communication	0.5 [s]
Initialization of AI model and segmentation algorithm	21 [s]

The message exchange connection process between MES/CLOUD-CLOUD/MES, managed from Node-Network, records times for the stock update of 1.3 s and for the download of order requests of 0.35 s. On the other hand, during the asynchronous serial communication between MES/ESP Master-ESP Master/MES, times for manufacturing orders sent to station (A) are recorded as 0.26 s and for the storage of local data received from station (D) as 0.24 s.

With the integration of the new technologies into the MPS 500 system, an optimized production line has been designed that, when receiving a mini-batch order, divides the task into two parallel processes. The first process handles product dispatch, starting at station (D) and ending at station (E), with an estimated time of 45 s per part. The second process, oriented to the manufacture or replenishment of parts, starts at station (A) and ends at station (D), with a cycle time of approximately 125 s. This significantly reduces order response times.

When the FC system is first requested to execute the part verification algorithm during the manufacturing process, the MFC node downloads the images and source code from container image repositories and saves them in its local memory, which takes approximately 5 s, while the coordination of loads, monitoring of resources and collection of results with the FCS nodes takes approximately 15 ms. On the other hand, for the analysis of the FC system performance results, it was essential to first evaluate the percentage consumption of the CPU during the execution of each algorithm. The results obtained showed the following percentages of CPU usage: 33% for the process of identifying edges and contours of parts, 54% for the process of comparison with the reference points of the facial regions previously stored in the dataset and 88% for the mathematical calculation. Based on these values, a conditioning was established by the MFC, which restricts the orchestration for any of the FCS nodes if the CPU consumption exceeds 60%; otherwise, it can orchestrate up to two processes per slave. To validate the correct operation of the FC system under this premise, the facial recognition and mathematical calculation processes were executed when station (C) was activated. This behavior was verified by means of the CPU usage readings of the FCS nodes, as shown in Figure 7.

According to the results of the load on the processors of the FCS nodes, an interesting orchestration dynamic is identified that distributes the workload between them. Figure 7 shows that there are fluctuations that indicate the execution of one or several processes in each FCS node, and there is also an approximate consumption of 28% in the idle state in certain periods due to the fact that they are in alert mode when attending the MFC requests. At the beginning, both nodes start with moderate CPU usage, ranging between 50% and 60%, corresponding to the independent execution of the computer vision algorithms, in which case no intensive use of resources is required. As time progresses between 20 and 40 s, a saturation close to 75% and 80% is observed, indicating the execution of the facial landmark and part quality control processes. In addition, the load distribution between both nodes is understood through an orchestration scheme coordinated by the MFC. Continuing on the timeline, just before the 40 s second mark, the onset of high CPU usage cycles by the FCS2 node over 90% is visualized, suggesting that the orchestration system identified processor consumption percentages on the FCS1 node over 60% at the time the mathematical calculation process was requested, there was efficient action by the MFC node to avoid oversaturation on the node and, consequently, a stable temperature regime of operation in the control units of the FCS nodes was achieved, as shown in Figure 8.

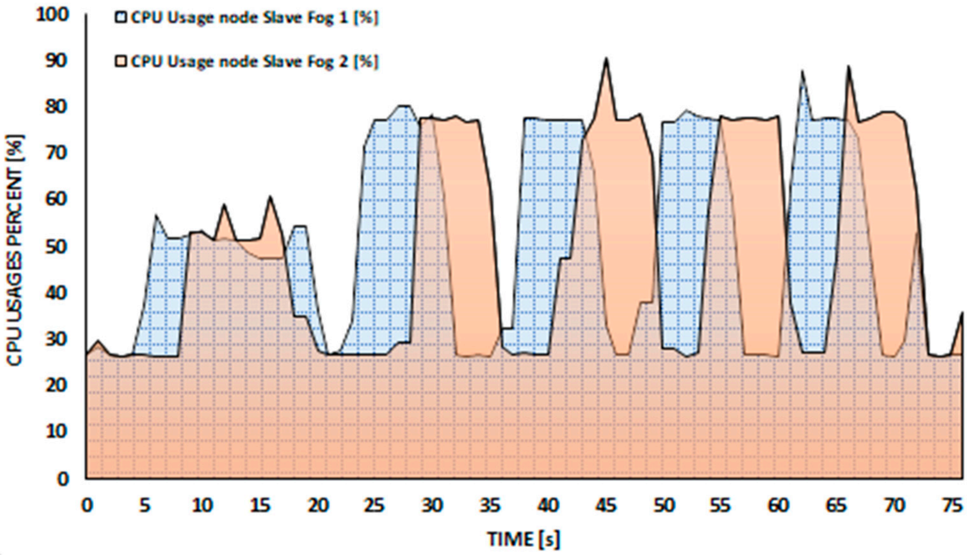

Figure 7. CPU performance on FCS nodes under different workloads.

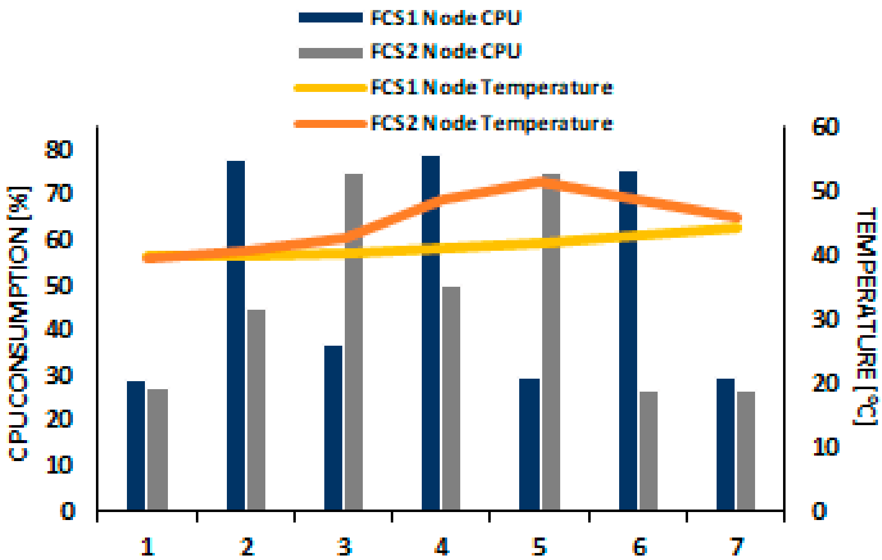

Figure 8. Relationship between CPU performance and temperature on two FC nodes under different workloads.

This orchestration pattern visualized in Figure 7 is fundamental to maintaining the stability of the system, especially at times when processing demands rose above the established CPU percentage, which was repeatedly observed between seconds 50 and 70. This situation confirms that the system efficiently managed the workload, and this can be evidenced in the temperature axis of the processing cards of the FCS nodes in Figure 8, which reached an average temperature of 43 °C according to the processes shown, ensuring the stability and effectiveness of the system in real operating conditions.

5. Discussion

This study implements the RAMI 4.0 framework to facilitate the transition from Industry 3.0 to Industry 4.0, highlighting the effectiveness of technologies such as fog computing and MES in real-time production management and resilience to connection failures. The results obtained, such as order response times and workload orchestration efficiency, demonstrate that the referential model is not only applicable in simulated or controlled environments but can be effectively adapted to real plants in SMEs with limited resources.

Compared to previous studies, this research on Industry 4.0 shows a clear advantage in simplifying technology integration in the context of SMEs by applying the reference model framework to optimize scalability and flexibility. In the reviewed approaches, common limitations are observed, such as the high dependence on robust infrastructure, the complexity of implementation in small companies and the high cost of integration with advanced technologies. This study has demonstrated how the use of fog computing (FC) in combination with a hybrid multi-level MES enables efficient orchestration of real-time tasks, distributing workloads without the need for expensive infrastructure.

The present implementation goes beyond the integration of MESs, as it also focuses on the optimization of communication and the resilience of the system to internet service failures, aspects often ignored in Industry 4.0 studies for SMEs. The integration of control devices (such as fog nodes) with applied AI for real-time image identification and segmentation is a distinctive contribution to this research. While previous studies were limited to proposing integration architectures, this work evaluates the orchestration of distributed workloads, prioritizing plant performance and thermal stability of processing nodes in the execution of CPU-intensive processes, as shown in Figure 7.

While previous studies applied RAMI 4.0 mainly in proof-of-concept or simulated environments, this work implements the architecture in a real plant, providing performance data on CPU usage, connection times and MES–cloud communication. Studies by [34,36] highlighted the lack of standardized methodologies and limitations in integration with existing systems, problems that this research addresses by coordinating between fog nodes and integrating legacy technologies. Performance in managing and orchestrating multi-level MES–FC processes in an industrial environment was also evaluated. Reconnection data between the MES and the cloud, with times of 1.5 to 1.7 s in case of outages, as well as stock update times (0.35 to 1.3 s), demonstrate an operational information flow in the face of connectivity failures. Comparatively, other studies, such as those by [35,43], report difficulties in interoperability with legacy systems and challenges in real-time data updates between MES and slave fog nodes, problems that this implementation has solved through the use of MQTT and Node-RED.

Furthermore, the approach was intended to convey the use of accessible tools, such as Node-RED and local databases, which ensure constant connectivity and monitoring capability, reducing latency and avoiding total dependence on the cloud. By employing technologies that maximize interoperability (e.g., MQTT and IoT communication protocols), the research improves the adaptability of manufacturing systems without sacrificing efficiency or significantly increasing operational costs, offering a more accessible and effective model for small industries transitioning to Industry 4.0. In other words, this study is nuanced in its ability to adapt to the specific context of SMEs, providing them with tools that drive flexible and scalable production in line with the RAMI 4.0 model, thus addressing several of the limitations observed in previous studies.

The main contribution of this study is its applied approach, which shows how an SME can use the referential model to scale up to Industry 4.0 in a gradual, efficient and cost-effective way. In contrast to studies such as [29], which consider transformation through end-user-oriented visual platforms, this research demonstrates that a focus on operational performance, supported by the integration of connectivity and processing technologies, is key for SMEs with infrastructure constraints. Data on connection times, CPU performance monitoring on FC nodes and MES responses to requests provide valuable information for future studies on the implementation of reference model 4.0 in industrial environments.

As this implementation focused on the integration of different technologies for production, certain aspects of RAMI 4.0, such as the complete product lifecycle and service management, were not addressed. In such an aspect and for a more complete intake, the implementation of a product lifecycle management (PLM) system at the product and service layer is recommended. In addition, an after-sales service system could collect customer feedback and improve future products, creating a continuous improvement cycle that reinforces alignment with reference model. However, this action requires the dense use of sensor technology or machine vision; in both cases, for its deployment, the economic resources of SMEs are important to consider. On the other hand, and moving towards the integration of technologies, traditional economic groups that do not use technology but are part of the global economy can integrate aspects such as holograms with natural language AI and gesticulation in modern manufacturing companies so that users can request their orders.

However, while the above recommendations may seem self-evident, it is critical to consider the principles that define an SME, especially in terms of its business infrastructure. Technology integration must be carried out within the limited capabilities of the processing control units, which highlights the need to implement a distributed computing network that streamlines and facilitates management along the entire production line. In contrast, during an expansion process, fog computing (FC) systems would work in conjunction with manufacturing execution systems (MESs), either from the edge of the network or via the cloud. This choice would, in part, be guided by the IEEE 1934 standard [53] and other applicable standards, depending on the reference model used.

6. Conclusions

The integration of information technologies (ITs) into operational technologies (OTs) in this study has been fundamental for the transition of a production plant from Industry 3.0 to Industry 4.0, taking the RAMI 4.0 framework as a reference structure. Through this integration, the manufacturing execution system (MES) was able to plan and manage production in an MPS, optimizing waiting times between operations and replenishment time at the storage station by approximately 30%. This parallel manufacturing process enables a 95% reduction in new order start-up times, substantially improving production efficiency and achieving integrated management between the dispatch and manufacturing stages.

The implemented hybrid architecture, which combines hierarchical levels in a single control card, facilitates fluid and agile communication between the fog computing (FC) nodes in the plant and between the MES and the cloud, achieving response times of approximately 15 ms and 1.7 s, respectively. This integration not only provides speed but also resilience, allowing the system to operate efficiently even under varying network conditions. However, it is emphasized that the performance of the control unit must be properly managed to avoid thermal overloads, which could slow down the processing speed and affect continuous operation. The FCS node orchestration has proven to be effective, maintaining operating temperatures between 45 °C and 55 °C, which ensures efficient energy consumption and reduces the need for additional cooling.

In terms of novel contribution, the flexibility of the RAMI 4.0 framework made it possible to integrate and orchestrate key technologies for smart manufacturing, aligning with Industry 4.0 objectives. This solution also presents a scalable and adaptable model for SMEs, enabling a modular and gradual expansion that fits their economic constraints. The implementation of distributed nodes offers SMEs a scalability option aligned with their resources and growth needs.

The proposed solution stands out for its flexibility and ability to integrate advanced technologies in a modular manufacturing environment. In addition, by implementing distributed nodes and a hybrid architecture, the system optimizes processing efficiency and allows for gradual expansion according to the company's resources. However, the initial infrastructure and training required to implement these technologies can be a challenge for SMEs facing budget constraints. In addition, while several layers of the RAMI 4.0 framework are covered, areas such as lifecycle management and value stream were not addressed in this implementation, given the focus on real-time production and operation. These aspects can be addressed in future expansions, taking advantage of the flexibility of the RAMI 4.0 framework and the modular structure of the proposed architecture.

Overall, this study provides a viable route for the modernization of traditional industries towards an Industry 4.0 model, with an adaptable architecture aligned with the RAMI 4.0 framework. The significant contribution of this research lies in its practical and scalable approach, which offers a solid foundation for the progressive growth of SMEs in the context of digitalization and advanced manufacturing.

Author Contributions: Conceptualization, W.O. and R.S.; methodology, W.O.; software, W.O. and R.S.; validation, W.O.; formal analysis, W.O.; investigation, W.O. and R.S.; resources, W.O.; data curation, W.O.; writing—original draft, W.O. and R.S.; writing—review & editing, W.O.; visualization, W.O.; supervision, R.S.; review, R.S.; project administration, W.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: This work was supported by Universidad Politécnica de Madrid (UPM) and Universidad Politécnica Salesiana (UPS).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Anumbe, N.; Saidy, C.; Harik, R. A Primer on the Factories of the Future. *Sensors* **2022**, *22*, 5834. [CrossRef] [PubMed]
2. Fuertes, G.; Zamorano, J.; Alfaro, M.; Vargas, M.; Sabattin, J.; Duran, C.; Ternero, R.; Rivera, R. Opportunities of the Technological Trends Linked to Industry 4.0 for Achieve Sustainable Manufacturing Objectives. *Sustainability* **2022**, *14*, 11118. [CrossRef]
3. Fakhar Manesh, M.; Pellegrini, M.M.; Marzi, G.; Dabic, M. Knowledge Management in the Fourth Industrial Revolution: Mapping the Literature and Scoping Future Avenues. *IEEE Trans. Eng. Manag.* **2021**, *68*, 289–300. [CrossRef]
4. Jung, S.; Kim, D.; Shin, N. Success Factors of the Adoption of Smart Factory Transformation: An Examination of Korean Manufacturing SMEs. *IEEE Access* **2023**, *11*, 2239–2249. [CrossRef]
5. Tortora, A.M.R.; Maria, A.; Valentina, D.P.; Iannone, R.; Pianese, C. A survey study on Industry 4.0 readiness level of Italian small and medium enterprises. *Procedia Comput. Sci.* **2021**, *180*, 744–753. [CrossRef]
6. Ciano, M.P.; Dallasega, P.; Orzes, G.; Rossi, T. One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: A multiple case study. *Int. J. Prod. Res.* **2021**, *59*, 1386–1410. [CrossRef]
7. Partearroyo, M.J.; De Pablos Heredero, C.; Lopez, A.M.; Gutierrez, L.M.A. Towards Industry 4.0: Impact on production strategies. *Procedia Comput. Sci.* **2023**, *219*, 563–570. [CrossRef]
8. Gallo, T.; Santolamazza, A. Industry 4.0 and human factor: How is technology changing the role of the maintenance operator? *Procedia Comput. Sci.* **2021**, *180*, 388–393. [CrossRef]
9. Noor-A-Rahim, M.; John, J.; Firyaguna, F.; Sherazi, H.H.R.; Kushch, S.; Vijayan, A.; O'Connell, E.; Pesch, D.; O'Flynn, B.; O'Brien, W.; et al. Wireless Communications for Smart Manufacturing and Industrial IoT: Existing Technologies, 5G and Beyond. *Sensors* **2023**, *23*, 73. [CrossRef]
10. Walia, G.K.; Kumar, M.; Gill, S.S. AI-Empowered Fog/Edge Resource Management for IoT Applications: A Comprehensive Review, Research Challenges, and Future Perspectives. *IEEE Commun. Surv. Tutor.* **2024**, *26*, 619–669. [CrossRef]
11. Gharibvand, V.; Kolamroudi, M.K.; Zeeshan, Q.; Çınar, Z.M.; Sahmani, S.; Asmael, M.; Safaei, B. Cloud based manufacturing: A review of recent developments in architectures, technologies, infrastructures, platforms and associated challenges. *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 93–123. [CrossRef]
12. Mikołajewski, D.; Czerniak, J.M.; Piechowiak, M.; Wegrzyn-Wolska, K.; Kacprzyk, J. The Internet of Things and AI-based optimization within the Industry 4.0 paradigm. *Bull. Pol. Acad. Sci. Tech. Sci.* **2024**, *72*, e147346. [CrossRef]
13. Garcia, A.; Oregui, X.; Arrieta, U.; Valverde, I. Methodology and Tools to Integrate Industry 4.0 CPS into Process Design and Management: ISA-88 Use Case. *Information* **2022**, *13*, 226. [CrossRef]

14. Burgos, A.; Alvarez, M.L.; Sarachaga, M.I.; Ozona, M. Metodología para el Desarrollo de Procesos de Automatización Según la Norma ANSI/ISA-88. 2022. Available online: https://ruc.udc.es/dspace/handle/2183/29703 (accessed on 27 July 2024).
15. Chohan, B.S.; Xu, X.; Lu, Y. MES Dynamic interoperability for SMEs in the Factory of the Future perspective. *Procedia CIRP* **2022**, *107*, 1329–1335. [CrossRef]
16. The, Y.-L.; Kuusk, A. Aligning IIoT and ISA-95 to Improve Asset Management in Process Industries. In *Lecture Notes in Mechanical Engineering, Proceedings of the 14th WCEAM Proceedings, Singapore, 28–31 July 2019*; Springer International Publishing: Berlin, Germany, 2021. [CrossRef]
17. Baptista, L.F.; Barata, J. Piloting industry 4.0 in SMEs with RAMI 4.0: An enterprise architecture approach. *Procedia Comput. Sci.* **2021**, *192*, 2826–2835. [CrossRef]
18. Hasbullah, H.; Bareduan, S.A. Capturing the Reality of Industry 4.0 Readiness Dimensions and Indicators in a Developing Country: An Analysis of Applying I4.0 in Indonesia. *S. Afr. J. Ind. Eng.* **2023**, *34*, 61–78. [CrossRef]
19. Leitao, P.; Karnouskos, S.; Strasser, T.I.; Jia, X.; Lee, J.; Colombo, A.W. Alignment of the IEEE Industrial Agents Recommended Practice Standard With the Reference Architectures RAMI4.0, IIRA, and SGAM. *IEEE Open J. Ind. Electron. Soc.* **2023**, *4*, 98–111. [CrossRef]
20. Junior, A.A.B.; Carrer, M.J. Adoption of Industry 4.0 technologies: An analysis of small and medium-sized companies in the state of São Paulo, Brazil [Adoção de tecnologias da Indústria 4.0: Uma análise com pequenas e médias empresas do estado de São Paulo, Brasil]. *Gest. Prod.* **2022**, *29*, e122. [CrossRef]
21. Bianchini, A.; Savini, I.; Andreoni, A.; Morolli, M.; Solfrini, V. Manufacturing Execution System Application within Manufacturing Small–Medium Enterprises towards Key Performance Indicators Development and Their Implementation in the Production Line. *Sustainability* **2024**, *16*, 2974. [CrossRef]
22. Li, Y.; Wang, L.; Chen, X.; Jin, R. Distributed data filtering and modeling for fog and networked manufacturing. *IISE Trans.* **2024**, *56*, 485–496. [CrossRef]
23. Prakash, V.; Savaglio, C.; Garg, L.; Bawa, S.; Spezzano, G. Cloud- and Edge-based ERP systems for Industrial Internet of Things and Smart Factory. *Procedia Comput. Sci.* **2022**, *200*, 537–545. [CrossRef]
24. Zheng, X.; Lu, J.; Kiritsis, D. The emergence of cognitive digital twin: Vision, challenges and opportunities. *Int. J. Prod. Res.* **2022**, *60*, 7610–7632. [CrossRef]
25. Lindner, M.; Bank, L.; Schilp, J.; Weigold, M. Digital Twins in Manufacturing: A RAMI 4.0 Compliant Concept. *Science* **2023**, *5*, 40. [CrossRef]
26. Pretel, E.; Moya, A.; Navarro, E.; López-Jaquero, V.; González, P. Analysing the Synergies between Multi-agent Systems and Digital Twins: A Systematic Literature Review. *Inf. Softw. Technol.* **2024**, *174*, 107503. [CrossRef]
27. Waclawek, H.; Schafer, G.; Binder, C.; Hirsch, E.; Huber, S. Digital Twins of Business Processes as Enablers for IT / OT Integration. In Proceedings of the IEEE International Conference on Industrial Informatics (INDIN), Lemgo, Germany, 18–20 July 2023. [CrossRef]
28. Ostrowski, A. RAMI 4.0 w transformacji cyfrowej przedsiębiorstwa-studium przypadku. *E-Mentor* **2022**, *93*, 54–63. [CrossRef]
29. Uslar, M.; Hanna, S. Model-Driven Requirements Engineering Using RAMI 4.0 Based Visualizations. Modellierung. 2018. Available online: https://api.semanticscholar.org/CorpusID:46861205 (accessed on 2 September 2024).
30. Bastos, A.; Coelho de Andrade, M.L.S.; Yoshino, R.T.; Dias Santos, M.M. Industry 4.0 Readiness Assessment Method Based on RAMI 4.0 Standards. *IEEE Access* **2021**, *9*, 119778–119799. [CrossRef]
31. Analyze Search Results. Available online: https://bibliotecas.ups.edu.ec:2226/term/analyzer.uri?sort=plf-f&src=s&sid=361bb6ca16eb5696ba4d9179f4f2c2b2&sot=a&sdt=a&sl=65&s=TITLE-ABS-KEY(Industry+4.0)+AND+PUBYEAR+%3E+2017+AND+PUBYEAR+%3C+2025&origin=resultslist&count=10&analyzeResults=Analyze+results (accessed on 29 August 2024).
32. Analyze Search Results. Available online: https://bibliotecas.ups.edu.ec:2226/term/analyzer.uri?sort=plf-f&src=s&sid=361bb6ca16eb5696ba4d9179f4f2c2b2&sot=a&sdt=a&sl=67&s=TITLE-ABS-KEY(rami+4.0)+AND+PUBYEAR+%3E+2017+AND+PUBYEAR+%3C+2025&origin=resultslist&count=10&analyzeResults=Analyze+results (accessed on 29 August 2024).
33. Raza, Z.; Haq, I.U.; Muneeb, M. Agri-4-All: A Framework for Blockchain Based Agricultural Food Supply Chains in the Era of Fourth Industrial Revolution. *IEEE Access* **2023**, *11*, 29851–29867. [CrossRef]
34. Binder, C.; Neureiter, C.; Lüder, A. Towards a domain-specific information architecture enabling the investigation and optimization of flexible production systems by utilizing artificial intelligence. *Int. J. Adv. Manuf. Technol.* **2022**, *123*, 49–81. [CrossRef]
35. Fett, M.; Kraft, M.; Wilking, F.; Goetz, S.; Wartzack, S.; Kirchner, E. Medium-Level Architectures for Digital Twins: Bridging Conceptual Reference Architectures to Practical Implementation in Cloud, Edge and Cloud–Edge Deployments. *Electronics* **2024**, *13*, 1373. [CrossRef]
36. Melluso, N.; Grangel-González, I.; Fantoni, G. Enhancing Industry 4.0 standards interoperability via knowledge graphs with natural language processing. *Comput. Ind.* **2022**, *140*, 103676. [CrossRef]
37. Cañas, H.; Mula, J.; Campuzano-Bolarín, F.; Poler, R. A conceptual framework for smart production planning and control in Industry 4.0. *Comput. Ind. Eng.* **2022**, *173*, 108659. [CrossRef]
38. Grefen, P.; Vanderfeesten, I.; Wilbik, A.; Comuzzi, M.; Ludwig, H.; Serral, E.; Kuitems, F.; Blanken, M.; Pietrasik, M. Towards Customer Outcome Management in Smart Manufacturing. *Machines* **2023**, *11*, 636. [CrossRef]
39. Urgese, G.; Azzoni, P.; van Deventer, J.; Delsing, J.; Macii, A.; Macii, E. A SOA-Based Engineering Process Model for the Life Cycle Management of System-of-Systems in Industry 4.0. *Appl. Sci.* **2022**, *12*, 7730. [CrossRef]

40. Senthilkumar, P.; Rajesh, K. Integrated Model-Based Engineering using Deep Learning with IIoT for Industry 4.0. *J. Inf. Technol. Manag.* **2023**, *15*, 112–123. [CrossRef]
41. Hernández, E.; Senna, P.; Silva, D.; Rebelo, R.; Barros, A.C.; Toscano, C. Implementing RAMI4.0 in Production–A Multi-case Study. In *Lecture Notes in Mechanical Engineering, Advances in Engineering Networks, Proceedings of the 12th CIO Proceedings, Spain, 12–13 July 2018*; Springer International Publishing: Cham, Switzerland, 2020; pp. 49–56. [CrossRef]
42. Hang, J.H.; Charles, D.S.; Gan, Z.H.; Gan, S.K.; Lim, Y.M.; Lee, W.P.; Wong, T.L.; Goh, C.P. Constructing a Real-Time Value-Chain Integration Architecture for Mass Individualized Juice Production. *Information* **2022**, *13*, 56. [CrossRef]
43. Tariq, B.; Salma, M.; Rajaa, B.; Jamal, B. RAMI 4.0 Framework applied to Industry 4.0 technologies deployment: Moroccan chemical industry use case. In Proceedings of the Colloquium in Information Science and Technology (CIST), Agadir-Essaouira, Morocco, 16–22 December 2023; pp. 384–388. [CrossRef]
44. *IEC 62264-1:2013*; Enterprise-Control System Integration—Part 1: Models and Terminology. International Electrotechnical Commission: Geneva, Switzerland, 2013.
45. *IEC 61512-1:2012*; Batch Control—Part 1: Models and Terminology. International Electrotechnical Commission: Geneva, Switzerland, 2012.
46. *IEC 62890:2016*; Life-Cycle Management for Systems and Products Used in Industrial-Process Measurement, Control, and Automation. International Electrotechnical Commission: Geneva, Switzerland, 2016.
47. Wagh, S.D.; Chiwande, S.N. Implementation of Manufacturing Execution System (MES) to Increase Productivity and Competitiveness in the Manufacturing Sector. *Int. J. Res. Appl. Sci. Eng. Technol.* **2024**, *12*, 3703–3714. [CrossRef]
48. Azarmipour, M.; Elfaham, H.; Gries, C.; Kleinert, T.; Epple, U. A Service-based Architecture for the Interaction of Control and MES Systems in Industry 4.0 Environment. In Proceedings of the 2020 IEEE 18th International Conference on Industrial Informatics (INDIN), Warwick, UK, 20–23 July 2020; pp. 217–222. [CrossRef]
49. Kolesnyk, Z.; Mezhenskyi, O.; Davykoza, O.; Kuchuk, H. Fog Computing Technology in Distributed Systems. Sistemi Upravlìnnâ, Navìgacìï Ta ZV'ÂZKU. 2024. Available online: https://journals.nupp.edu.ua/sunz/article/view/3276 (accessed on 11 September 2024).
50. Cañas, H.; Mula, J. A general overview of the Industry 4.0 concept for production management and engineering. In *Advances in Engineering Networks*; de Castro, R., Giménez, G., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 45–51.
51. Oñate, W.; Sanz, R. Analysis of Architectures Implemented for IIoT. *Heliyon* **2023**, *9*, e12868. [CrossRef]
52. Kim, D.; Kim, H. Continuous Technological Modernization Strategy in Defense Acquisition: Overcoming the Obsolescence Barrier. Han'gug bang'wi san'eob haghoeji. *J. Korea Def. Ind. Assoc.* **2023**, *30*, 65–74. [CrossRef]
53. *IEEE 1934-2018*; Standard for Adoption of OpenFog Reference Architecture for Fog Computing. Institute of Electrical and Electronics Engineers: New York, NY, USA, 2018.